Appendix M

AUTOMATED COASTAL FLOOD MONITORING NETWORK AND WARNING SYSTEM

Feasibility Analysis and Design Recommendations

April 1986

Prepared For:

CONNECTICUT DEPARTMENT OF ENVIRONMENTAL PROTECTION

NATURAL RESOURCES CENTER

Prepared By:

L.R. JOHNSTON ASSOCIATES

Westport, CT

Connecticut: Coastal Zone Management Program

COVER PHOTOGRAPH: Clinton, Connecticut, September 27, 1985 during Hurricane Gloria.

Taken by Howard Sternberg, Connecticut Department of Environmental Protection, Natural Resources Center

AUTOMATED COASTAL FLOOD MONITORING NETWORK AND WARNING SYSTEM

Feasibility Analysis and Design Recommendations

April 1986

Prepared For:

CONNECTICUT DEPARTMENT OF ENVIRONMENTAL PROTECTION

NATURAL RESOURCES CENTER

Prepared By:

L.R. JOHNSTON ASSOCIATES

Westport, CT

ABSTRACT

This study was initiated by a Connecticut interagency Committee on Automated Flood Warning to: (1) develop specifications for establishing an automated coastal flood monitoring network which would be compatible with the existing statewide automated riverine flood warning system; and (2) evaluate the feasibility of establishing a State coastal flood forecast and warning system.

There are currently five automated gages in operation along the Connecticut coast that measure and record tide and storm surge levels. At present, data from only one of these gages (Bridgeport) is used as input into the National Weather Service's (NWS) forecasts and warnings. There are no automated wave gages or other long-term measurements of waves along the Connecticut coast.

All coastal flood forecasts and warnings are provided by the NWS, and most of these are based on meteorological data from large scale weather systems and specific storms (such as hurricanes). NWS has developed a state-of-the-art numerical model for forecasting storm surge during hurricanes and tropical storms, and this model has recently been applied in Long Island Sound. In contrast, NWS techniques for forecasting wave heights and storm surge in Long Island Sound during extratropical storms are based on limited data and simple statistical models. NWS forecasts and warnings usually are not site specific, and may apply to the entire Connecticut coast, to all of Long Island Sound, or to a large subarea such as eastern Long Island Sound or western Connecticut.

While it is technically feasible for the State of Connecticut to develop its own models for wave and extratropical storm surge forecasts, such an approach would be expensive and duplicate NWS responsibilities. This report recommends that the State work with and encourage NWS to upgrade its forecast techniques for wave heights and extratropical storm surge. It also recommends that the State supplement NWS regional forecast data with real-time, site specific storm surge and wave collected data through a network of automated coastal gages.

A low cost network of automated, real-time gages to measure tides and storm surge could be deployed that would be compatible with the existing automated riverine flood warning system. Adding wave measurement capability to the network would significantly increase the cost of the system. The addition of wave data also would require some compromise in either the compatibility of the coastal monitoring network with the existing riverine system or the type of wave data collected. Further work is needed to detail the specific system design if wave data is to be collected as part of the coastal monitoring network.

A series of automated tide and storm surge gages at five permanent sites is recommended, along with two additional "roving" gages that can be used to correlate data at many other coastal locations with data collected at one or more of the permanent sites. Three of the permanent gage locations and the two "roving" gages could be used for wave measurements.

Development of the coastal monitoring network can improve NWS coastal forecasts and warnings, provide State and local emergency management personnel with needed site specific data on actual storm surge and wave conditions, and benefit other potential users such as coastal researchers and recreational and commercial boaters.

CONTENTS

CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

ACKNOWLEDGMENTS

The authors wish to thank the many individuals in Federal, State and local agencies and private organizations who provided information for this report. Special thanks are extended to the members of the subcommittee on Coastal Flood Warning who supervised this project:

Ted Hart, Connecticut Department of Environmental Protection, Water Resources Unit

Ralph Lewis, Connecticut Department of Environmental Protection, Natural Resources Center

Todd Mendell, National Weather Service, Northeast River Forecast Center

Tom Oullette, Connecticut Department of Environmental Protection, Coastal Area Management

Cynthia Rummel, Connecticut Department of Environmental Protection, Natural Resources Center

Allan Williams, Connecticut Department of Environmental Protection, Natural Resources Center

Principal authors of this report are Larry R. Johnston, L. R. Johnston Associates, and David G. Aubrey, Ph.D., Woods Hole Oceanographic Institution. Additional assistance was provided by Wayne Spencer of WHOI and Stanley Humphries, consulting coastal geologist.

Funding for this project was provided by the Federal Emergency Management Agency, State Assistance Program, under a Cooperative Agreement with the Connecticut Department of Environmental Protection. The substance and findings of this work are dedicated to the public. The author and publisher are solely responsible for the accuracy of all statements and interpretations. Such statements and interpretations do not necessarily reflect the views of the Federal government.

1.0: INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

Automated flood warning systems were originally developed by the National Weather Service (NWS) during the late 1970's in order to increase the amount of warning time available to people who live and work in the floodplains of rivers subject to flash floods. This NWS system, known as ALERT (Automated Local Evaluation in Real-Time), relies on recent advances in microprocessor and computer technology to provide accurate, real-time information on precipitation amounts and stream level rises within a river basin.

The Connecticut Department of Environmental Protection (DEP) became convinced of the potential value of an ALERT system in Connecticut, and in 1982 it formed an interagency Committee on Automated Flood Warning (CAFW). This committee developed a Master Plan for a statewide automated flood warning system known as ASERT (Automated State Evaluation in Real-time), to be developed jointly with local ALERT systems. The initial phases of the ASERT system are currently being installed, along with two pilot ALERT systems.

Within each river basin that is part of the Connecticut ASERT/ALERT system, a series of automated precipitation gages and stream gages collect information on rainfall amount and intensity and amount and rate of rise in river levels. This data is telemetered by VHF radio to NWS, State and local receiving stations equipped with a microcomputer and software for analyzing, displaying and storing the information. The system has the capability to combine the rainfall and streamflow data with a hydrologic model of each basin, and to automatically predict expected flood levels and times. Information on predicted flood levels can be compared to maps which delineate the areas that will be innundated as flood waters reach different heights. Appropriate warnings may then be issued for specific areas at risk.

Although the ASERT/ALERT system was designed for application in river basins, DEP officials began to consider whether this same concept could be applied to coastal flood warnings. Unable to identify a similar coastal system in operation elsewhere, DEP submitted a proposal to the Federal Emergency Management Agency (FEMA), and in 1985 received a grant to carry out a study with two primary objectives:

(1) develop specifications for establishing an automated coastal flood monitoring network which is compatible with the statewide ASERT system, and

(2) evaluate the feasibility of establishing a coastal flood warning system utilizing information from the monitoring network.

1.2 METHODS

In order to design the monitoring network and evaluate the feasibility of a warning system, it was necessary to evaluate the following:

(1) Existing tide, storm surge and wave monitoring systems in use along the Connecticut shore.

(2) Existing NWS forecast and warning procedures for storm surge and wave heights.

(3) The current status of coastal flood warning procedures in Connecticut.

(4) Available technology that could be employed to collect flood data and improve existing flood forecasts and warnings.

(5) Other potential uses of information generated by a coastal monitoring network.

(6) Costs and benefits of implementing a State operated monitoring network and warning system.

Investigation of these and other issues resulted in findings which permitted the formulation and evaluation of numerous alternative monitoring networks; more detailed design of selected networks, each with different capabilities and degree of compatibility with the ASERT system; and recommendations for providing coastal flood warnings. The major findings are highlighted in this summary, and a full discussion is included in the main body of the report.

1.3 FINDINGS

1.3.1 Existing Tide, Storm Surge and Wave Measurements

Staff gages which can be read visually are located at many locations along the Connecticut coast, primarily at ports, marinas and Coast Guard stations. These staff gages do not provide a continuous or permanent record of actual tide levels.

Recording tide gages are presently operated at five sites along the Connecticut coast. These gages record the actual tide and storm surge levels on either a continuous basis or at selected short intervals.

(1) Thames River estuary at New London. Owned and operated by the National Ocean Service (NOS).

(2) Poquonock River estuary in Groton. Owned and operated by the U.S. Geological Survey (USGS) in cooperation with DEP.

(3) Mouth of the Connecticut River at Old Saybrook. Owned and operated by the USGS in cooperation with DEP.

(4) Bridgeport Harbor. Owned and operated by the NOS. The Bridgeport Weather Service Office (WSO) also uses this gage.

(5) Stamford Harbor. Owned by the U.S. Army Corps of Engineers (COE) and operated by the USGS.

Presently, only the NWS recordings from the NOS gage in Bridgeport Harbor are actually used as input to any storm surge forecasts and warnings.

There are no wave gages permanently operating along the Connecticut coast. Wave gages have been installed for short periods as part of research projects.

1.3.2 NWS Storm Surge and Wave Height Forecast and Warning Procedures

The NWS is responsible for issuing all coastal storm forecasts and flood warnings. In large part, these forecasts and warnings are based on meteorological and oceanographic data generated by national and regional NWS data collection systems. Locally generated data often provide only a minor input to these forecasts and warnings. The NWS uses four different procedures for preparing storm surge and wave height forecasts and issuing warnings for the Connecticut coast and Long Island Sound, depending upon the type of weather condition.

(1) For hurricanes, surge forecasts and warnings are prepared by the National Hurricane Center (NHC) in Miami. Hurricane forecasts and warnings are not modified by local NWS offices, although they may be supplemented with local information that is more geographically specific. No separate wave height forecast is prepared.

(2) For tropical storms, surge forecasts and warnings are prepared by the NHC, but may be modified by the Weather Service Forecast Office (WSFO) in New York City, if warranted by local conditions, as well as supplemented with more detailed information. No separate wave height forecast is prepared.

(3) For extratropical storms, storm surge forecasts are prepared by the NWS National Meteorological Center (NMC) in Silver Springs, Maryland. The New York WSFO reviews these surge forecasts and modifies them, as appropriate, based on local observations of actual wind, pressure and storm surge conditions. The New York WSFO also prepares a separate wave height forecast, and issues a coastal marine forecast and warning for Long Island Sound (LIS).

(4) Wave height forecasts for non-storm conditions are also prepared by the New York WSFO and routinely issued as part of the coastal marine forecast.

1.3.3 Connecticut Coastal Flood Warning Procedures.

NWS forecasts and warnings for storm surge and wave conditions in LIS are disseminated by a combination of NWS, Coast Guard, State agencies, local officials, and news media. NWS warnings are provided directly to the Coast Guard, Connecticut Office of Civil Preparedness (OCP), Connecticut State Police (CSP), some municipalities, and major news media through official emergency communications links of the National Warning System (NAWAS) and NOAA Teletype. State officials in turn relay NWS warnings through the State warning network directly to all municipalities and to selected news media.

NWS forecasts and warnings reach the general public through the NOAA Weather Radio (NWR), Coast Guard marine radio (for mariners) and, most importantly, through the news media, especially T.V. and radio. More specific warnings, such as evacuation notices for residents of vulnerable coastal areas, are provided by local officials through such means as sirens, public address systems, car-mounted loudspeakers, door-to-door notification, telephone calls, and neighborhood associations. In some communities, local cable T.V. and radio stations may issue specific information provided by the municipal civil preparedness offices.

1.3.4 Available and Emerging Technology.

NUMERICAL MODELS. Complex numerical models for predicting storm surge and wave action have become feasible with the availability of massive data processing capability of modern computers. An NWS model for predicting storm surge during hurricanes and tropical storms, called SLOSH (Sea, Lake and Overland Surge from Hurricanes), recently became operational for LIS. No equivalent models for predicting storm surge during extratropical storms (northeasters), or for predicting wave action, are presently operational for LIS.

INSTRUMENTATION. The recent availability of powerful microprocessors has opened up new possibilities for real-time and near real-time data collection, transmission and processing. The miniature size and low power requirements of these microprocessors permit large amounts of data to be collected almost instantaneously at remote locations, including subsea sites. Sophisticated electronics have also enabled development of water level measurement sensors, such as pressure transducers and acoustic devices, that do not have moving parts and do not require contact with the water surface. Data may be processed at field locations or transmitted via telephone lines, VHF and UHF radio, and satellite for processing at central receiving stations.

Unfortunately, many of the recent technological advances which permit real-time collection and transmission of data are not based on industry-wide, uniform standards. Therefore, not all available systems and instrument components are compatible with one another. Efforts have just been initiated at the federal level to establish instrument standards with which future federal procurements in this field must comply. The present lack of standardization complicates the design of a coastal flood monitoring network for Connecticut, and the study requirement to design a monitoring network compatible with the existing ASERT system somewhat limits the instrumentation that can be considered and the capabilities of an ASERT compatible system.

PROGRAMS. Federal, state and local governments have developed programs which utilize the new modeling and instrumentation technology for navigation, weather forecasting, flood warnings, research and other purposes. The following federal agency programs will have a direct impact on coastal flood data and warnings in LIS and along the Connecticut shore:

(1) The NWS, FEMA, and COE jointly, in cooperation with coastal states, are using the SLOSH model to estimate storm surge heights for any likely track and intensity of a hurricane along the Atlantic and Gulf coasts. Maps are prepared delineating coastal areas that will be flooded during different hurricanes.

(2) The NOS is planning to upgrade its entire network of permanent tide gages to permit acquisition of real-time tide and storm surge data and to make this data available to NWS and other users.

(3) While the new NOS system is being developed and installed, the NWS is temporarily installing new telemetry equipment at selected NOS tide gage sites which will permit near real-time transmission of tide and storm surge elevations to NWS offices responsible for weather forecasts and warnings.

The NOS upgrade of its tide gage network is still in a program development and testing phase, and lack of a final choice by NOS for the total system configuration and instrumentation to be used makes it unclear if a Connecticut system will ultimately be entirely compatible with future NOS and NWS technology.

Other programs developed by federal, state and local governments, often in concert with private industry, provide valuable experience for evaluating the feasibility of a Connecticut flood monitoring network and warning system. The following programs which use real-time data are particularly relevant:

(1) New York Harbor Tidal Gage System. This system of four automated water level gages in New York Harbor is designed primarily as a navigation aid, but is also used by the NWS to help prepare local forecasts for LIS.

(2) Delaware Bay Navigation Project. Similar to, but more ambitious than the New York Harbor system, this project incorporates a numerical model of tides and currents in Delaware Bay, and is capable of predicting tide levels and currents up to 12 hours in advance.

(3) West Coast Wave Monitoring Network. A network of offshore wave buoys and nearshore pressure gages along the west coast of the U.S. (and one off the coast of North Carolina) provides data for evaluating longshore sediment transport and coastal erosion. Data is also used by the NWS to develop wave forecasts and provide real-time wave information in marine weather bulletins. The system is operated by the Scripps Institute of Oceanography (SIO), and it would be possible for Connecticut to link up with this network for processing of LIS wave data.

1.3.5 Potential Uses of Data from Monitoring Network.

The primary intended uses of data from a coastal monitoring network are:

(1) to improve both the extent and timeliness of the data base used to prepare coastal storm forecasts and warnings, and

(2) to provide local communities with near real-time information on actual storm surge and wave heights compared to forecasts.

Other potential uses were also identified, including:

(1) aid to navigation. Real-time tide and wave data available during both storm and non-storm periods could benefit pleasure boaters and commercial shipping interests, particularly harbor pilots. Accurate tide data is also useful for dredging projects and hydrographic surveys.

(2) research. Storm surge and wave data are needed for research on coastal processes within Long Island Sound, including circulation patterns needed for understanding movement of pollutants.

(3) coastal engineering. Empirical data on storm surge and waves are also needed to improve the design and construction of coastal structures, including protective structures such as groins, jetties, breakwaters, and seawalls, and others such as marinas, docks, and residential and commercial buildings.

1.3.6 Costs and Benefits.

COSTS: Development of a coastal flood monitoring network will be more costly than a comparable ASERT/ALERT system operating within a river basin. Many coastal network components are relatively more expensive because they must be capable of withstanding the harsh coastal environment. In addition, initial installation costs will be greater than in a riverine setting, and maintenance must be performed more frequently and at greater costs. Depending upon the final design selected, the coastal network may be able to utilize some existing radio repeaters and base station components of the ASERT system and existing recording tide gages, thereby holding down costs. Estimated initial costs of a coastal monitoring network range from about $50,000 for a network that measures only tides and storm surge and makes maximum use of existing instrumentation, to over $400,000 for a network that also measures full wave characteristics and employs all new instrumentation.

The State of Connecticut may be able to reduce significantly its costs of installing and operating a coastal monitoring network by entering into cooperative agreements with other agencies such as NWS, NOS, COE, and USGS that have an interest in the information to be produced by the network. It may also be possible to spread the costs among more than one State agency. Depending upon the final design of the network, the Bureau of Waterways of the Department of Transportation (DOT) and the University of Connecticut (UCONN) may derive significant benefits from the data, and could be approached for sharing the costs of initial network installation and/or operation and maintenance. It may also be feasible to charge user fees for access to data by private groups such as harbor pilots, dredging operations, researchers, design engineers, etc.

The costs of developing a suitable extratropical storm surge model for LIS will be substantial. Modification of an existing model and model verification can be accomplished for a cost of between $50,000 and $100,000. Development of a large set of scenarios to predetermine areas to be innundated from a particular storm may cost an additional $150,000 or more. Development of a suitable numerical wave model may cost about $30,000.

BENEFITS. Because of the large number of potential users (Table 1.1), benefits from a monitoring network and near real-time dissemination of data will be substantial, though difficult to quantify.

(1) Coastal flood warnings can be enhanced, permitting reductions in property losses and unnecessary evacuations:

   (a) The availability of more precise and timely data from several locations along the coast should enable the NWS to improve the accuracy and timeliness of forecasts and warnings

USERS	BENEFITS
Coastal residents and property owners	Surge and wave height data for design purposes.
Municipal agencies	Actual conditions for storm surge and wave heights
Office of Civil Preparedness	Actual conditions for storm surge and wave heights
DEP, Natural Resources Center	Data for inclusion in its natural resources inventory
DEP, Water Resources Unit	Hydrologic studies of the coastal reaches of river basins; revisions to Flood Insurance Studies
DEP, Water Compliance Unit	Water quality studies of LIS, including currents, movement of pollutants, circulation patterns, etc.
DEP, Coastal Area Management	Longshore sand transport, coastal erosion, evaluation of coastal structures
University of Connecticut and educational institutions	Short- and long-term research studies on coastal processes, circulation, currents, etc.
National Weather Service	Storm surge forecasts and present levels; wave height forecasts and current conditions; verification of forecast models
Federal Emergency Management Agency	Revisions to Flood Insurance Studies; Hurricane Preparedness Studies
Corps of Engineers	Hurricane Preparedness Studies; dredging of federally maintained channels; port and harbor studies; other coastal studies
National Ocean Service	Short- and long-term sea level variation
Coast Guard	Sea surface and weather conditions, tide levels
Harbor pilots and marine industries	Accurate tide levels for movement of vessels in and out of harbors
Pleasure boaters and marina owners	Timely information on wave conditions
Coastal engineers	Storm surge and wave energy and spectral data for design of coastal structures

TABLE 1.1: User Benefits from a Real-Time Coastal Monitoring Network

(b) The availability of accurate, real-time data for specific coastal locations should enable community officials to supplement regional NWS forecasts and warnings with more precise local warnings.

(c) The benefits of improved warnings can be increased still further if the information on storm surge and wave heights is combined with appropriate inundation maps.

(2) Navigation improvements:

(a) Commercial shippers can save money by loading vessels to capacity, reducing waiting time for harbor entry or exit, and avoiding groundings.

(b) Commercial fishermen can locate best fishing areas and avoid groundings.

(c) Pleasure boater and marina operators can make more informed decisions about safe boating conditions and channel depths.

(3) Research data:

(a) Surge and wave data for improved engineering design of coastal structures.

(b) Improved understanding of sand movement and beach erosion.

(c) Tide, surge and wave data for improved understanding of water quality, including movement of oil spills and other pollutants.

1.4 CONCLUSIONS AND RECOMMENDATIONS

1.4.1 Conclusions.

(1) The present system of issuing forecasts and warnings for coastal storms and flooding is less than optimal. Although existing warning procedures appear adequate to avoid loss of life and serious injury, improved warnings which provide more precise information on the timing, location, and extent of flooding would allow further reductions in property losses and avoid some unnecessary evacuations. There is room for improvement in most aspects of the total system and at every level of government, including:

(a) quantity and quality of data used in preparing forecasts

(b) timeliness of data availability

(c) use of additional data in forecast models

(d) use of new and improved models for forecasting storm surge and wave heights

(e) methods of disseminating forecasts and warnings to local communities

(f) development of innundation maps that can be used with flood warnings

(f) methods of providing warnings and instructions to residents of coastal floodplains

<u>(2) Although improvements in each of these areas are certainly possible, not all are equally feasible at the present time. Nor will potential improvements in each area yield equal results in reducing flood losses.</u>

(a) Only limited improvements appear feasible to the existing NWS forecast and warning system for hurricanes and tropical storms. Because hurricane warnings are already conservative (i.e. attempt to warn of the most severe likely impact), the limited improvements will probably have little effect on reducing flood losses, especially in Connecticut where the coastal flood zone is relatively small.

(b) More significant improvements in storm forecasts and flood warnings appear possible for extratropical storms (northeasters).

(c) The most significant improvements should result from supplementing NWS regional forecasts with more precise information for particular geographic areas.

<u>(3) The primary responsibility for providing storm, storm surge, and wave forecasts and warnings should remain with the NWS</u>. Historically, issuance of coastal storm forecasts and warnings have been the exclusive province of the NWS. Technological advances have now made it possible for other levels of government and private concerns to prepare forecasts and issue warnings, although they must still rely upon the NWS for much of the essential data. This ability makes it attractive to seek ways of supplementing or replacing NWS procedures that do not take advantage of the latest technology or do not provide the desired site specific information. Nevertheless, there are compelling reasons to continue reliance upon the NWS as the primary provider of forecasts and warnings.

(a) The NWS has a long history of providing reasonably accurate forecasts and credible warnings.

(b) Current and planned improvements in the programs of NWS and other federal agencies will make possible improvements in NWS forecast capabilities.

(c) It would be very expensive for the State to develop and operate its own coastal storm forecast system.

(d) Even if the State did develop its own forecasting system, the NWS would still issue its own forecasts and warnings.

(e) There is need for consistency of information during emergencies. Conflicting information coming from different sources during emergencies has long been recognized as a major cause of improper response or lack of response by those located in areas at risk.

(4) The State can initiate several actions which will result in improved forecasts and warnings. State activities should:

(a) enhance the capabilities of federal agencies to perform data collection, forecast and warning responsibilities; and

(b) supplement the federal agencies' regional forecasts and warnings with more detailed information in specific geographic areas regarding the extent and timing of anticipated flooding.

To avoid unnecessary expenditures, public confusion over differing messages, and conflicts with federal agencies, the State should not:

(a) duplicate federal programs and responsibilities, or

(b) issue information that conflicts with NWS warnings.

(5) Development of a coastal flood monitoring network for real-time measurement of tide and storm surge levels and which would be compatible with the existing ASERT system is feasible and would provide recognizable benefits, both quantifiable and non-quantifiable.

(a) Improved flood forecasts and warnings.

(b) Improved navigation.

(c) Improved data for design of coastal structures.

(6) Collection of wave data, while providing important information for flood warnings and other uses, would not be completely compatible with the ASERT system.

(a) Collection of wave data can be made compatible with ASERT, but requires some compromises on the quality of wave data and/or the ASERT system.

(b) A separate wave data network could be established to supplement the ASERT compatible tide/storm surge network.

(c) A tide/storm surge/wave network could be established that would be completely independent of ASERT.

1.4.2. Recommendations.

(1) The State should proceed with developing a coastal flood monitoring network. Important aspects of this network include:

(a) Utilize the existing network of tide gages in LIS, including planned improvements, to the extent possible.

(b) Add new tide, storm surge, and wave measurement stations where needed.

(c) Make data from the State network available to local communities, the NWS and other users.

(d) Make decisions on which optional network (described in 1.5 below) should be implemented, based on budgetary and other considerations.

(2) The State should train local officials in the proper use of the monitoring network.

(a) Use and maintenance of local receiving (base) stations.

(b) Intrepretation of tide, storm surge, and wave data from the monitoring network and how to use the data to supplement NWS forecasts and warnings.

(3) At the present time, the State should not develop its own storm surge or wave models for Long Island Sound. Instead, it should:

(a) Work with the NHC, FEMA, and the COE to ensure that the SLOSH model for LIS is used most effectively.

(b) Encourage the NWS to develop a numerical storm surge model for extra-tropical storms for LIS.

(c) Encourage the NWS to develop an improved wave forecast model for LIS.

1.5 RECOMMENDED MONITORING NETWORKS

1.5.1. Number and Location of Gages.

Empirical data suggest that storm surge along the coast can be adequately monitored with five stations:

(1) Stonington - New London reach: area of historical uncertainty.

(2) Waterford - East Haven reach: constant slope in storm surge.

(3) New Haven area: local maximum in storm surge.

(4) Milford - Bridgeport reach: low point in storm surge.

(5) Stamford - Greenwich reach: area of highest surge.

Wave hindcasting techniques suggest that at least three wave stations should be established:

(1) Madison - Old Lyme reach: subject to both easterly swells and local winds.

(2) New Haven area: mid-coast; subject to long fetch winds from both east and west.

(3) Stamford - Greenwich area: mostly local winds; complex shoreline and offshore bathmetry; subject to long easterly fetch.

1.5.2. Optional Monitoring Network Designs.

In addition to the number and location of gage stations, the optional designs for a monitoring network reflect consideration of: type of water level and wave sensors; compatibility with ASERT; utilization of existing equipment, programs and procedures; uses of data in addition to storm warnings; costs of establishing and maintaining the system.

ASERT COMPATIBLE NETWORK

Three principle options for an ASERT compatible network are available.

(A) Tide and Storm Surge Measurements Only: Use existing recording tide gage stations at:

(1) Stamford Harbor
(2) Bridgeport Harbor
(3) Mouth of Connecticut River (Old Saybrook)
(4) Thames River (New London)

Add a new station at:

(5) New Haven Harbor.

In addition, two "roving" gages should be temporarily (approximately one year) installed at various locations along the coast to provide good correlation with the permanent stations. These roving gages could be placed in harbors and other easily accessible locations.

(B) Tide, Storm Surge and Wave Measurements: Use existing recording tide gage stations at:

(1) Bridgeport Harbor
(2) Mouth of Connecticut River (Old Saybrook)
(3) Thames River (New London)

New stations should be added at:

(4) Stamford Harbor Breakwater
(5) New Haven Harbor Breakwater

As with the previous option, two roving gages should also be installed at various locations along the coast. However, the roving gages should be installed at locations along the open coast to permit measurement of wave characteristics. Because installation in open water locations is more expensive and wave characteristics are highly variable, these gages should remain in each location at least two years or until a good set of wave data are obtained.

Because ASERT/ALERT accepts data on a random or event reporting basis, in order to collect wave data and still have the network be compatible with the ASERT system, wave data or system reliability must be compromised:

(1) Only average wave height and wave length are obtained instead of the usual significant wave height, significant wave period, and wave spectral data.

(2) Significant wave height, significant wave period, and wave spectral data can be obtained, but only processed data can be sent to ASERT base stations, and the raw wave data (useful for research and verification purposes) may be lost.

(3) Multiple transmissions of wave data are sent to the base station, increasing the chance of that data getting through, but crowding the airways.

(C) Separate Storm Surge and Wave Networks To collect uncompromised wave data and still utilize the ASERT microcomputer and software (some ASERT software modifications will be needed for any of the alternatives considered), a separate data transmission system is needed for wave data. Two options exist: a one-way communications network (like ASERT), and a two-way communications network that would permit changing sampling frequency of wave sensors from the base station. If the ASERT transmission system is not used, wave directional data could also be included providing a proper wave gage is installed. Another option would be to link the wave data transmission system to the Scripps Institute of Oceanography (SIO) computer via telephone lines for processing of wave data by SIO.

DATA COLLECTION NETWORK INDEPENDENT OF ASERT If the State decides that ASERT compatibility is less important than collecting the full range of wave data, a totally independent monitoring network with two-way communications could be established that also utilizes a separate computer and specialized software for processing wave data.

COSTS Costs for the least expensive alternative (ASERT compatible, no wave data) would be approximately $50,000 and range upward to more than $400,000 for the independent network.

DATA AVAILABILITY All data will be transmitted by VHF radio to existing base stations at the Northeast River Forecast Center (NERFC) in Bloomfield and the State DEP offices in Hartford. In addition, it is recommended that new base stations be established at the Bridgeport WSO and Hartford WSO, and at the two State warning points (OCP and CSP) in Hartford. Each local community that desires to participate in the system would need to purchase its own base station. Arrangements should be made so that data can also be accessed by modem and telephone lines by users who do not need a base station.

2.0: TIDES AND TIDAL FLOODING IN LONG ISLAND SOUND

In order to design a coastal flood monitoring network which will accurately measure storm surge and wave action along the Connecticut shore, it is necessary to understand how normal tidal fluctuations and storm induced flooding occur in Long Island Sound. This section reviews available information on tides, storm surge and waves in Long Island Sound and along the Connecticut coast.

2.1 TIDAL DATUMS

Storm surge, heights of structures, soundings, and other coastal measurements must have numerical values above or below some reference base. The logical choice for the base is the ocean surface. But, since the ocean (and land) surface moves up and down, it must be "fixed" in order to become a suitable reference base. The result of mathematically fixing the ocean surface in terms of an observed tidal phenomenon is called a tidal datum. (1)

Many tidal datums are in use and are often confused by coastal residents and others. The official tidal datums for the U.S. are established by the NOS (2). The tidal datums and related terms most relevant to a flood monitoring network are defined below and illustrated in Figure 2.1.

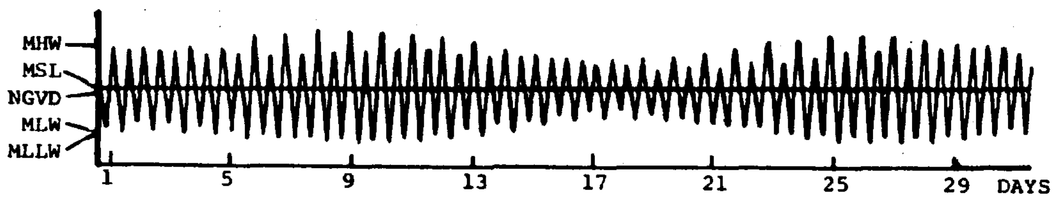
National Tidal Datum Epoch -- The specific 19-year period adopted by the NOS as the official time segment over which tide observations are taken and reduced to obtain mean values for tidal datums. It is necessary for standardization because of periodic and nonperiodic trends in sea level. The present National Tidal Datum Epoch is 1960 through 1978.

Mean Low Water (MLW) -- The average of all the low water heights observed over the National Tidal Datum Epoch[1].

Mean Lower Low Water (MLLW) -- The average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch. Mean Lower Low

---

[1] For stations with shorter series, simultaneous observational comparisons are made with a control tide station in order to derive the equivalent datum of the National Tidal Datum Epoch. (2)



MHW	Mean High Water
MSL	Mean Sea Level
NGVD	National Geodetic Vertical Datum (1929)
MLW	Mean Low Water
MLLW	Mean Lower Low Water

FIGURE 2.1: Relative Heights of Several Common Tidal Datums (Semidiurnal Tide)

Water is the tidal datum for soundings and depth contours on nautical charts[2].

Mean High Water (MHW) — The average of all the high water heights observed over the National Tidal Datum Epoch[1]. Mean High Water is the reference base for structure heights, bridge clearances, etc. The shoreline on USGS quadrangle maps is approximately MHW.

National Geodetic Vertical Datum (NGVD) of 1929 — A fixed reference adopted as a standard geodetic datum for elevations determined by leveling. The datum was derived for survey from a general adjustment of the first-order leveling nets of both the United States and Canada. In the adjustment, mean sea level was held fixed as observed at 21 tide stations in the United States and 5 in Canada. NGVD (formerly referred to as Mean Sea Level, and shown as such on older USGS quadrangle maps) is the standard datum of elevations throughout the U.S. Because there are many variables affecting sea level, and because the geodetic datum represents a best fit over a broad area, the relationship between the geodetic datum and local mean sea level is not consistent from one location to another in either time or space. For this reason, NGVD should not be confused with mean sea level.

All other elevations are referenced to NGVD, which has an elevation of 0.0. For example, a value for MHW of 3.0 feet means that MHW is 3.0 feet above NGVD. An increase in relative sea level such that MHW increases 0.4 feet from one National Tidal Datum Epoch to another would mean that MHW had risen 0.4 feet with respect to NGVD, and the adjusted value of MHW would be 3.4 feet. The elevation of flood levels on coastal flood maps are given as elevation above NGVD.

Mean Sea Level (MSL) — The arithmetic mean of hourly heights observed over the National Tidal Datum Epoch. Shorter series are specified in the name; e.g., monthly mean sea level and yearly mean sea level.

2.2 TIDAL VARIATION IN LONG ISLAND SOUND

Tides in Long Island Sound are semidiurnal with two high tides and two low tides occurring each tidal (lunar) day (5). A tidal day is the time of rotation of the earth with respect to the moon, and its mean value is approximately

[2] NOS recently changed the tidal datum for the Atlantic coast from mean low water to mean lower low water, which is the datum in use on the Pacific and Gulf coasts. Although new nautical charts will have the chart datum lowered from mean low water to mean lower low water, actual sounding figures, isobath and other information will not be changed due to: a) offsetting effects of rising sea level with change from 1941-1959 datum to 1960-1978 datum; b) thickness of lines on nautical charts and bathymetric maps; and c) roundoff procedures and accuracies in datum determinations, hydrographic surveying, and nautical charting. (3)

equal to 24.84 hours. (2) Hence, each high tide follows the previous high tide by approximately 12 hours and 25 minutes.

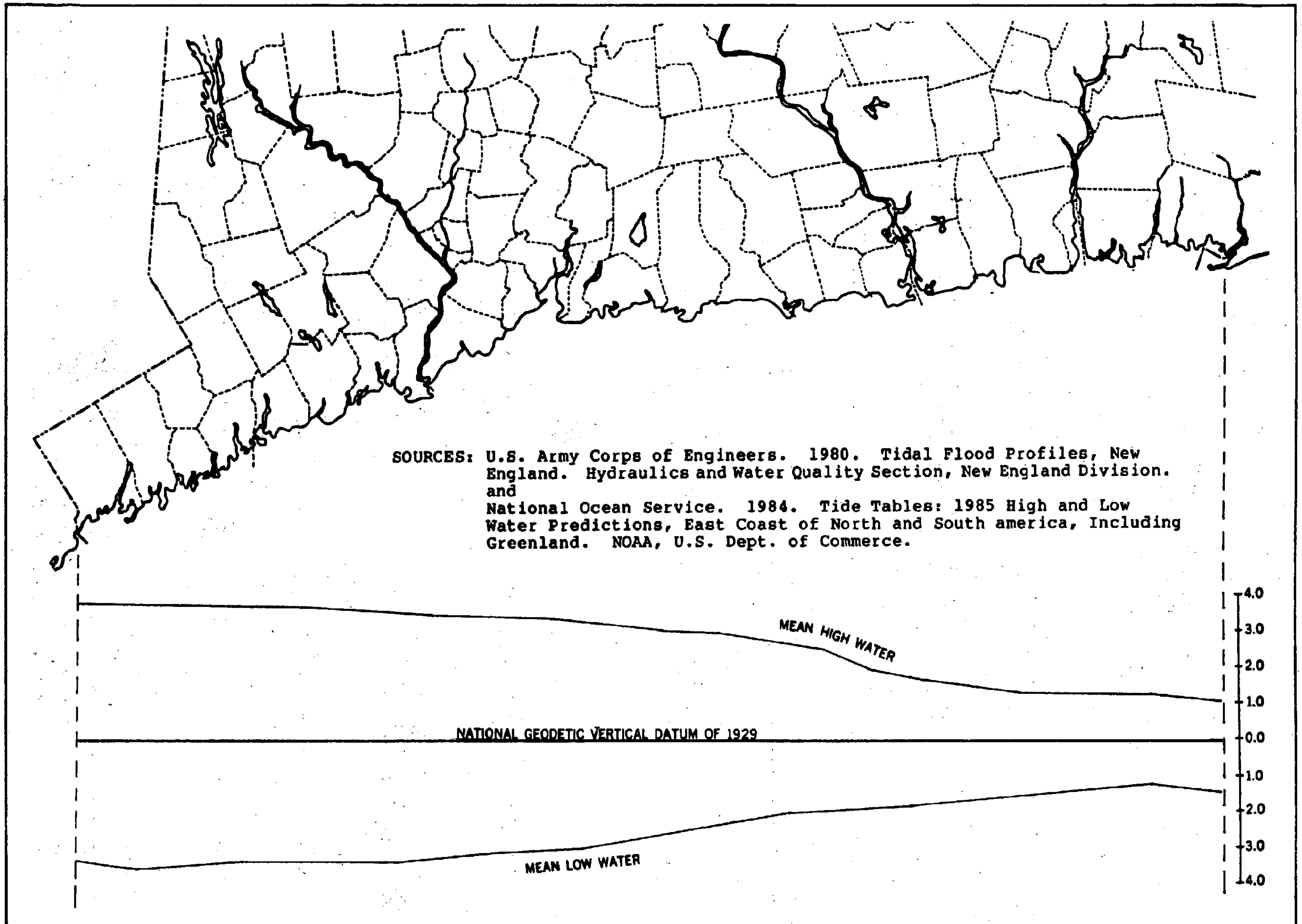
Because of the Sound's size and shape, it amplifies the oceanic tide, and the tidal range in the western Sound is larger than the tidal range in the east. At Greenwich, for example, the average tidal range is about 7.2 feet while at Stonington the range is only about 2.5 feet (6). High and low tides also occur at different times throughout the Sound. High tide at Greenwich occurs approximently two hours later than high tide at Stonington (7). Figure 2.2 shows the variation in normal tide ranges at selected points along the Connecticut coast.

Just as Long Island Sound affects the timing and amplitude of oceanic tides, the bays and estuaries along the Connecticut coast also modify the timing and amplitude of local tides within the Sound. Along most of the coast these local effects are minor, but become significant in the upper tidal reaches of the Connecticut and Thames rivers. (7)

2.3 RELATIVE SEA LEVEL RISE

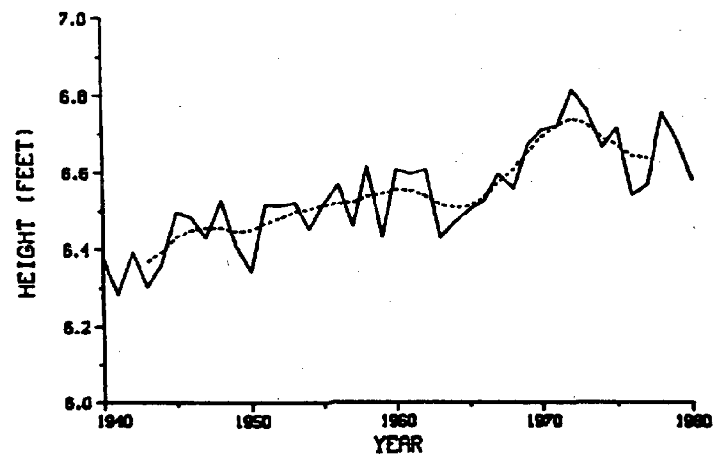
Relative sea level has been rising over the past 15,000 years as the earth's climate has warmed, and as the earth has undergone tectonic activity. From tide measurements, the NOS has developed trends in the relative rise of yearly mean sea level for the period 1940 through 1980. The average for the entire U.S. coast is 1.3 mm/year. For the northern east coast the rate is considerably higher at 2.6 mm/year (see Figure 2.3). Figure 2.4 shows the increase in yearly mean sea level for the two long-term gages on the north shore of Long Island Sound. (1). These stations and other data for northern Long Island Sound show relative sea level to have increased about 20-25 cm over the past 100 years (a rate of 2.0-2.5 mm/year). (8)

Recent research (102,103) has found that relative sea-level rise along the U.S. northeast coast is due not only to global increases in sea level (due to thermal expansion of the ocean surface and melting of glaciers in response to heating of the earth's surface), but also to a large effect from



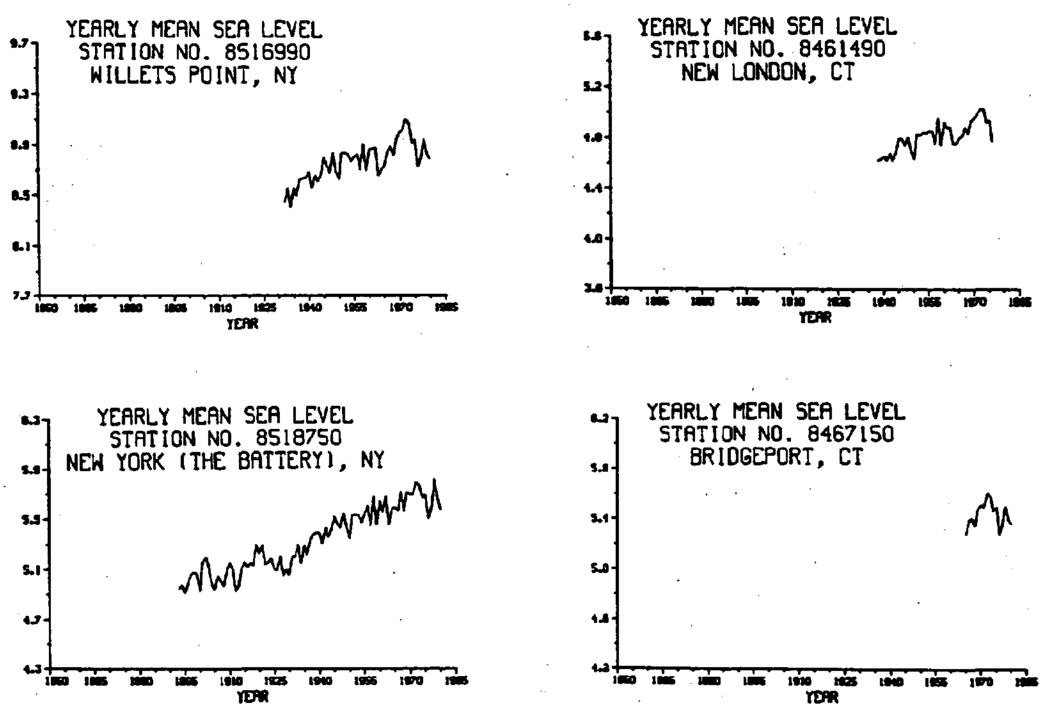
SOURCES: U.S. Army Corps of Engineers. 1980. Tidal Flood Profiles, New England. Hydraulics and Water Quality Section, New England Division.
and
National Ocean Service. 1984. Tide Tables: 1985 High and Low Water Predictions, East Coast of North and South america, Including Greenland. NOAA, U.S. Dept. of Commerce.

FIGURE 2.2: Tidal Ranges Along the Connecticut Coast



SOURCE: Hicks, Steacy D. 1983. Sea Level Variations for the United States, 1855-1980. National Ocean Service, NOAA, U.S. Dept. of Commerce.

FIGURE 2.3: Mean Sea Level Rise for Northern East Coast



SOURCE: Hicks, Steacy D. 1983. Sea Level Variations for the United States, 1855-1980. National Ocean Service, NOAA, U.S. Dept. of Commerce.

FIGURE 2.4: Yearly Mean Sea Level Recorded at Long Term Tide Gages in Long Island Sound

isostatic adjustment. As the North American glaciers melted over the past 10-15 thousand years, land previously covered by glaciers has adjusted to removal of the weight of the glacial mass. Land which was formerly depressed below the glaciers is now rebounding; so relative sea level has been falling. Along the edges of the glacial mass, which includes the Long Island Sound region, land was elevated somewhat, and has been falling, so relative sea level has been rising. Thus, Connecticut relative sea levels are a combination of global processes and localized response to retreat of the glacial mass.

This relative rise in sea level is expected to continue over the next century, and the rate of increase is anticipated to increase, but the future rate of relative sea level rise is uncertain. Recent reports by the Environmental Protection Agency (EPA) in 1984 (9) and the National Academy of Sciences (NAS) in 1983 (10) examined the effect of atmospheric concentrations of carbon dioxide and trace gases (methane, chlorofluorocarbons, etc.) on relative sea level rise. Increased concentrations of these gases may act to trap the long-wave radiation re-radiated from the earth's surface, resulting in heating of the atmosphere -- commonly known as the greenhouse effect. This heating of the atmosphere in turn would warm the ocean's surface, causing it to expand and produce a relative sea-level rise, and perhaps melt the glaciers (this effect is much more uncertain).

Although it cannot be asserted with any confidence what the effects on sea level will be, there are several estimates of these effects. The NAS anticipates a rise in sea-level of 70 cm (2.3 feet) would occur over the next century, given plausible models of atmospheric warming. EPA provides several estimates of global sea level rise to the year 2100 (Table 2.1). Under EPA's high scenario, sea level would rise 345 cm (11.3 feet) by 2100. Under their conservative scenario, sea level would rise 56 cm (1.9 feet) by 2100. EPA feels that a global sea level rise between 144 cm (4.8 feet) and 217 cm (7 feet) by the year 2100 is most likely. By the year 2000, EPA's more likely estimates are that sea level will rise between 8.8 cm (0.29 ft) and 13.2 cm (0.43 ft). EPA also estimates that along most of the Atlantic and Gulf coasts of the U.S, the rise will be 18 to 24 cm (0.6 to 0.8 feet) more than the global average. The greatest changes will not occur until after the turn of the century. All projections are significantly higher than current trends in sea level

SCENARIOS OF FUTURE SEA LEVEL RISE
(centimeters)

Scenario	Year 2000	2025	2050	2075	2100
High	17.1	54.9	116.7	211.5	345.0
Mid-range high	13.2	39.3	78.9	136.8	216.6
Mid-range low	8.8	26.2	52.6	91.2	144.4
Low	4.8	13.0	23.8	38.0	56.2
Current Trends	2.0-3.0	4.5-6.8	7.0-10.5	9.5-14.3	12.0-18.0

SOURCE: Hoffman, John S., et. al. 1983. Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs. U.S. Environmental Protection Agency.

TABLE 2.1: EPA Scenarios of Future Sea Level Rise

rise.

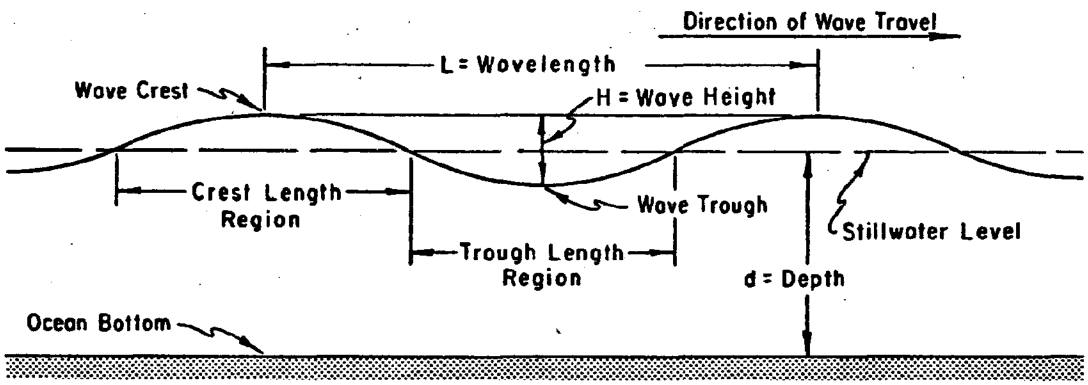
2.4 TIDE, STORM SURGE, AND WAVE MEASUREMENTS IN LONG ISLAND SOUND

2.4.1 Waves

WAVE CHARACTERISTICS. Waves, created by wind blowing over the surface of the water, are the major factor in determining the geometry and composition of beaches, and cause most of the damage in coastal areas, including coastal erosion and damage to structures. Waves are usually defined by their height, length, and period (Figure 2.5), which are determined by the fetch (the distance the wind blows over the sea in generating the waves), the wind speed, the length of time the wind blows, and the decay distance (the distance the wave travels after leaving the generating area). Generally, the longer the fetch, the stronger the wind; and the longer the wind blows, the larger the waves.

Wave action is extremely complex. The wind simultaneously generates waves of many heights, lengths, and periods as it blows over the water. In areas of shallow water, the water depth also affects the size of waves. Waves are subject to refraction (bending), depending on the wavelength in relation to water depth; diffraction (energy transfer along the crest of the wave); and reflection (as they encounter natural and manmade barriers. As a wave moves toward shore, it reaches a depth of water so shallow that the wave collapses or breaks. This depth is equal to about 1.3 times the wave height.

Because of bottom friction and wave scattering, there is considerable alongshore variability in wave behavior. This variability is obvious to anyone who has observed waves breaking on the shore. The variability exists in both space and time. The time-variability reflects the development of the storm, including the wind speed, wind direction, and location of the storm center or front. The spatial variability reflects the dissipation and scattering of waves as they travel towards shore. As an example, the sheltered areas behind Fishers Island will experience distinctly different waves than the shoreline not in the lee of the island.



SOURCE: U.S. Army Coastal Engineering Research Center. 1977. Shore Protection Manual, Volume I. Corps of Engineers, Dept. of the Army.

FIGURE 2.5: Wave Characteristics

For modeling and engineering design purposes, the "significant wave height" and "significant wave period" are often used, and may be considered to represent the average height and period of the dominant waves. More complex measurements of the "energy spectra" and "directional spectra" of waves take into account the many different types and directions of waves that occur at any particular time. Because of their highly technical nature, no further description of these quantative measures of wave characteristics is provided in this report. (11)

WAVE MEASUREMENTS. There are no long-term measurements of wave characteristics for Long Island Sound. No wave buoys or other instruments for measuring wave characteristics have been permanently installed in the Sound. In its 1976 study (12) of the effects of coastal storms on the Connecticut coastline, the Corps of Engineers (COE) found that no wave measurements or statistical wave data were available for the area. Limited wave measurements for specific locations and for short durations have been obtained as part of coastal research studies performed at the University of Connecticut (13) and the State University of New York at Stony Brook (14). As input to its LIS Marine Weather Bulletin,the NWS may receive reports from Coast Guard stations and ships concerning observed wave heights (15).

The COE (12) has estimated that the maximum height of waves breaking at exposed locations along the Connecticut shoreline with tides three feet or more above mean high water ranges from about three to eight feet, with the possibility of larger waves during very high tides. As part of the recent update of Flood Insurance Studies, FEMA contractors found that for a storm surge with a return frequency of 100 years, wave heights would range from 5.5 to 6.5 feet above the stillwater level at exposed locations. The maximum wave crest was determined to be 18 feet above NGVD at Greenwich. Predicted wave heights were about one foot higher in the western portions of the Sound than in the east. (16)

2.4.2 Tides and Storm Surge

STORM SURGE. Storm surge is defined as the difference between the observed water level and that which would have been expected at the same place in the absence of the storm. Surge height during a particular storm depends primarily on the following processes, although other factors also exert some influence: (6)

(1) Atmospheric pressure differences. The sea level surface is elevated in response to the low pressures associated with storms. In the open ocean, a pressure drop of 33.86 millibars (one inch) will lead theoretically to a 13 inch rise in sea surface elevation (7).

(2) Wind set-up. Wind stress on the water surface will cause water levels to increase along the fetch in a downwind direction. Wind stress, and hence, wind setup are proportional to the square of the wind velocity. Wind set-up is also enhanced by decreasing depth. (18)

(3) Wave set-up. Breaking waves create turbulance and actually move water nearer shore, resulting in increased height of the water level surface in this area. Wave set-up may account for as much as 3.3 to 6.4 feet of storm surge height at a beach. (19)

(4) Rainfall. Intense rainfall can lead to an increase of water levels, especially in estuaries.

(5) Storm motion effects. The intensity of the storm, the speed of storm movement, and the angle of the storm track at the shoreline can affect storm surge (11,17).

(6) Shoreline configuration and basin bathymetry. In general, configurations which favor an increase in the range of astronomical tide will also favor an increase of storm surge heights (11).

TIDE AND STORM SURGE MEASUREMENTS. As described below, considerably more data is available on tide and storm surge levels for LIS than for wave characeristics.

Staff Gages. Coast Guard stations and many marinas and port terminals have installed tidal staff gages that can be read visually. The COE has installed a tide staff gage in the ports of New London, New Haven, and Bridgeport, and in Stamford Harbor at the Hurricane Barrier. Most of these gages are located on a pier or dock in a protected portion of the harbor. Readings are not usually taken at regular intervals, and records of readings are not generally maintained. Often, temporary tide staff gages are installed for special projects, such as dredging. (20,21,22,23,24,25)

Recording Gages. Recording tide gages are presently in operation at five locations along the Connecticut Coast (Figure 2.6):

(1) Thames River estuary at New London. Owned and operated by the National Ocean Service (NOS).

(2) Poquonock River estuary in Groton. Owned and operated by the U.S. Geological Survey (USGS) in cooperation with DEP.

(3) Mouth of the Connecticut River at Old Saybrook. Owned and operated by the USGS in cooperation with DEP.

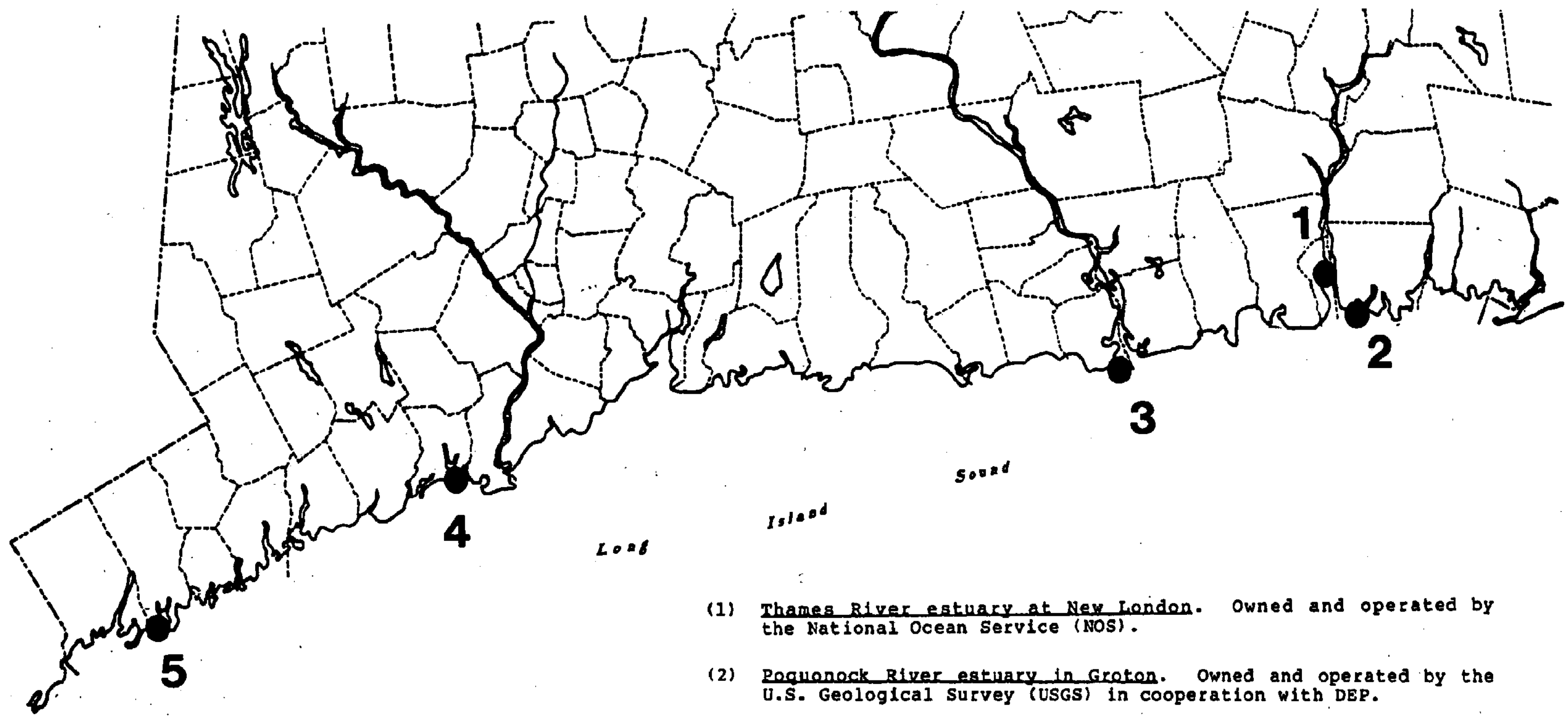
(4) Bridgeport Harbor. Owned and operated by the NOS. The Bridgeport Weather Service Office (WSO) also uses this gage.

(5) Stamford Harbor. Owned by the U.S. Army Corps of Engineers (COE) and operated by the USGS.

National Ocean Service. The NOS owns and operates the tide gages at New London and Bridgeport (NOS has an additional recording gage in Long Island Sound at Willets Point on the north shore of Long Island (7)). These stations are part of the NOS network of stations known as NWLON (National Water Level Observation Network), which includes 225 permanent gage stations. The New London station is located at State Pier No. 1 in the Thames River (Figure 2.6 (1)). It has been in operation since 1938. The Bridgeport gage is located at Hitchcock Marina in Bridgeport Harbor (Figure 2.6 (4)). It was originally installed in 1932, but data is not available for the entire period. (7,26,27,28,29)

Figure 2.7 illustrates a typical NOS station installation. Each station includes a primary recording gage and a reference staff gage. The reference staff is connected by precise leveling to nearby bench marks. Generally, the station also includes a backup recording gage.

The primary gage is an electro-mechanical Analog-to-Digital Recorder (ADR) (typically a Fisher & Porter or Leupold & Stevens type) which measures water level by means of a float and wire attached to a spring-loaded drive (Figure 2.8). As the water rises and falls, the drum rotates and turns a shaft. A mechanical pin assembly, driven by a timer, converts the analog signal to a digital reading by punching the elevation into a time sequenced paper tape (Figure 2.9). Water levels are recorded every six minutes. To



(1) Thames River estuary at New London. Owned and operated by the National Ocean Service (NOS).

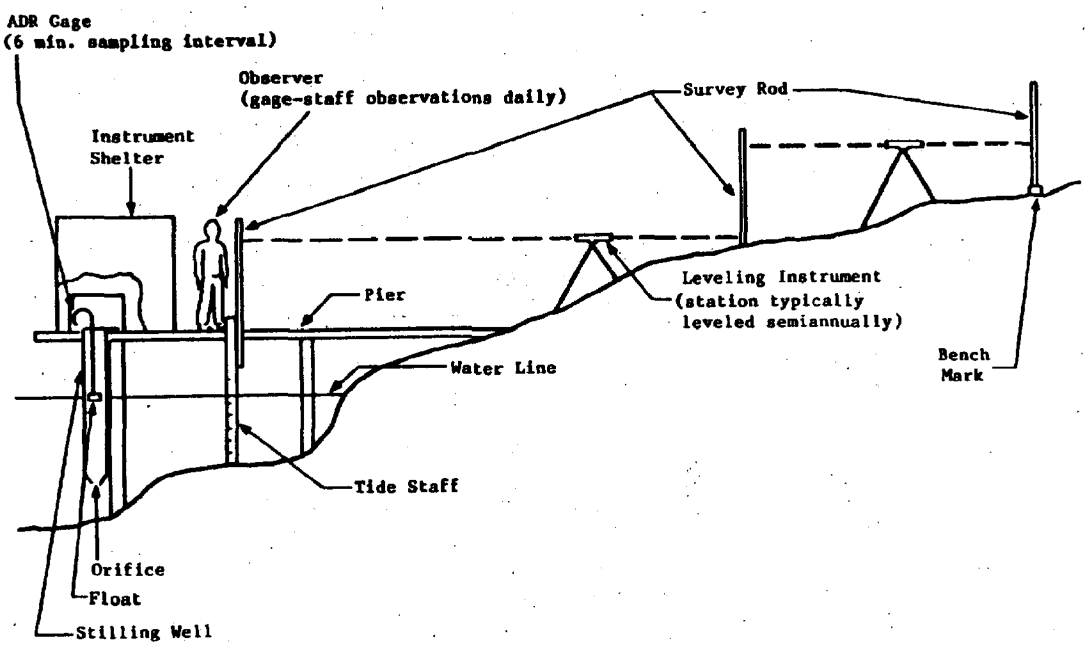
(2) Poquonock River estuary in Groton. Owned and operated by the U.S. Geological Survey (USGS) in cooperation with DEP.

(3) Mouth of the Connecticut River at Old Saybrook. Owned and operated by the USGS in cooperation with DEP.

(4) Bridgeport Harbor. Owned and operated by the NOS. The Bridgeport Weather Service Office (WSO) also uses this gage.

(5) Stamford Harbor. Owned by the U.S. Army Corps of Engineers (COE) and operated by the USGS.

FIGURE 2.6: Existing Recording Tide Gages in Long Island Sound



SOURCE: Deibel, Lawrence E., and Barbara A. Zumwalt. 1985. Next Generation Water Level Measurement System Program. By the Mitre Corporation for National Ocean Service, NOAA, Dept. of Commerce.

FIGURE 2.7: Typical NOS Tide Station Installation

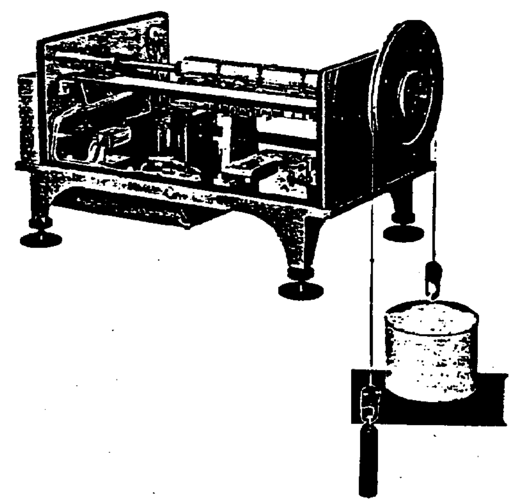
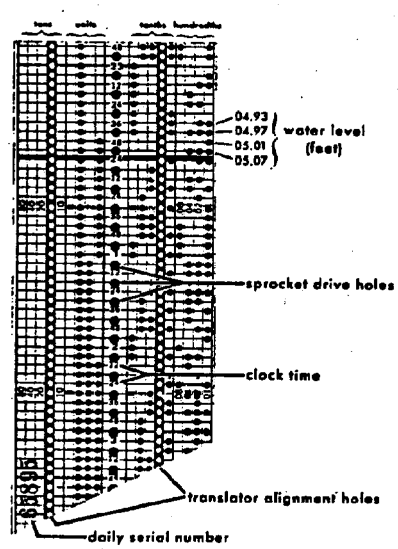


FIGURE 2.8: Typical Analog-to-Digital Recorder



SOURCE: Coast and Geodetic Survey. 1977. Manual of Tide Observations. Publication 30-1, U.S. Dept. of Commerce.

FIGURE 2.9: Recording Tape Showing Time Divisions and Binary-Coded Digital Punch Out

reduce wave effects on the reading, the float and wire are mounted in a vertical pipe with a small orifice at the bottom, referred to as a stilling well. Water level heights are recorded with a resolution of 0.001 foot, and an accuracy of about 0.01 foot.

An analog recording pressure gage (bubbler gage) is often used to provide backup data (Figure 2.10). These gages rely on changes in water pressure to indirectly measure the rise and fall of water level. Nitrogen is bubbled through an underwater tube, and the pressure encountered activates a bellows which in turn moves a pen across a sheet of recording paper mounted on a rotating drum (Figure 2.11). Accuracy ranges from +/- 0.1 foot in low range areas to +/- 0.5 foot in high range areas.

Five times per week, local NOS tide observers check the tide stations and compare the gage readings with visual water readings on the reference staff. The observer enters the staff reading into a special log form, and also marks the correct time directly on the recording charts. The punched paper tapes, analog recordings, and comparative staff readings are mailed to NOS headquarters at the end of each month by the tide observer. Data are analyzed and recorded by NOS and permanently retained. Anyone may request (purchase) tidal records for these stations from NOS. Data are generally not available until at least three months after it has been transmitted to NOS headquarters. NOS annually publishes a set of tide tables (7) for these and other NOS stations that provide predicted high and low tides for the entire year. NOS also prepares hourly tide level predictions for the two permanent stations, which can be obtained for any month of the year. (27,30,31)

National Weather Service. The NWS does not operate any tide gages of its own in Connecticut. It does, however, obtain data from the NOS gage at Bridgeport. The NWS has installed a connection (Bristol Metameter) to the NOS ADR gage which transmits tide levels automatically to the Bridgeport WSO by telephone, where they are recorded on a continuous strip chart. The strip charts are retained only a few months by the Bridgeport WSO, but daily high and low tides and hourly tide levels are manually transferred from the strip chart to printed forms, which are retained for several years. (32,33,34)

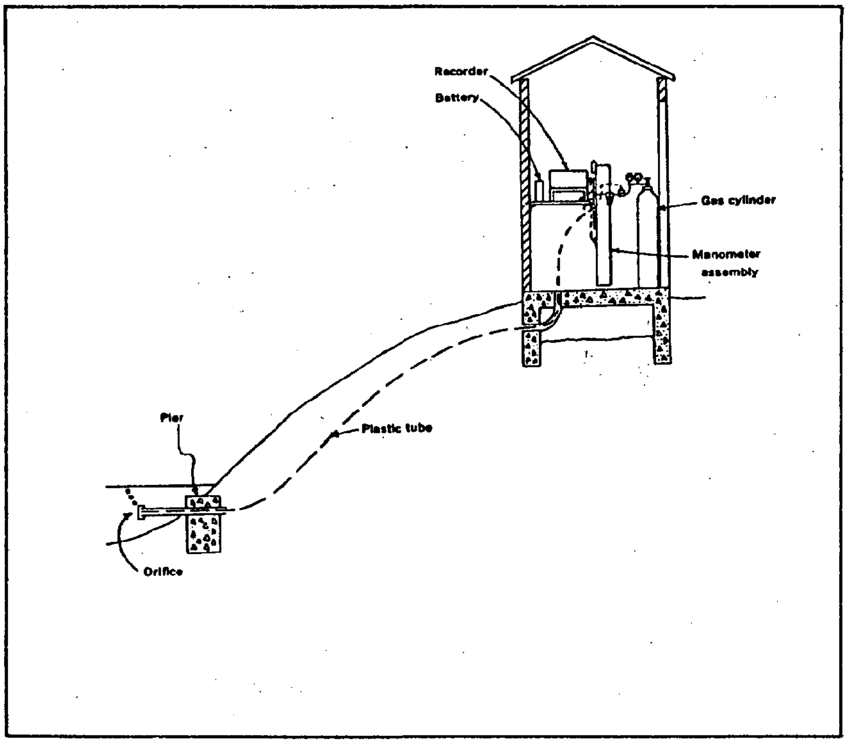
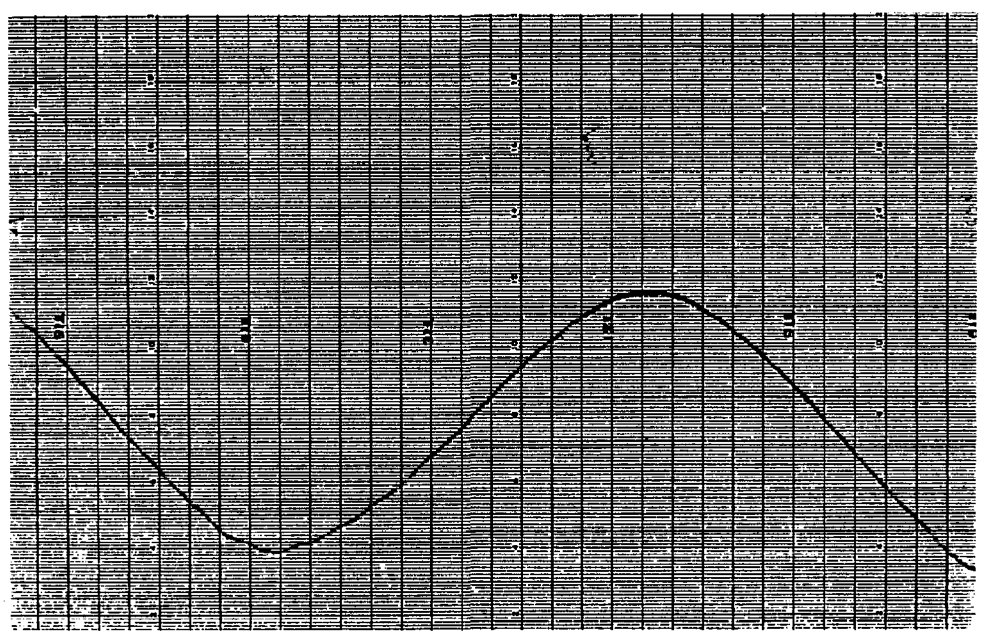


FIGURE 2.10: Typical Bubbler Gage Installation



SOURCE: Bridgeport Weather Service Office, Stratford, CT.

FIGURE 2.11: Typical Tide Record from Analog Recorder

Corps of Engineers/U.S. Geological Survey. Recording tide gages are also located in Stamford Harbor. These gages are owned by the COE for use in conjunction with operation of the Stamford Hurricane Barrier. The gages are maintained by the USGS as part of a cooperative agreement. One gage is located outside the hurricane barrier and another inside the barrier to record differences in tide levels when the barrier is closed. Both are pressure gages of the bubbler type, similar to the backup gages used by NOS. USGS records the data at 15 minute intervals on punched paper tape. The tape is collected by USGS personnel approximately every six weeks and processed for inclusion in annual reports of water records in Connecticut. Unpublished data are available at the USGS office in Hartford. Records are available since October 1972. The COE records tide levels on a continuous strip chart within the station house. Charts are stored at the Stamford office for three years. The Stamford gage is equipped with a Stevens Telemark unit which transmits a coded tide level reading by telephone. The telephone number is unlisted, and is used primarily by the USGS and the COE. NOS provides the COE with predictions of hourly tide levels at Stamford Harbor. (25,35,36,37,38,39)

The COE used to operate tide gages at Block Island and the Bridgewater Lighthouse at Old Saybrook in an attempt to correlate tides and storm surge at those locations with tides and storm surge at Stamford, and to provide increased warning time for operation of the hurricane barrier. These gages operated from approximately 1972 - 1977. Tide levels were recorded at three hour intervals and did not record high and low tides. The COE found poor correlation with the tide levels at Stamford, and because the gages offered no prediction capability, they were removed. The data have not been retained. (39,40)

U.S. Geological Survey/State of Connecticut. Under its cooperative agreement with the State of Connecticut to collect streamflow records, the USGS owns and operates two water level gages in tidal locations: at the mouth of the Poquonock River in Groton (Figure 2.6 (2)), and in Old Saybrook at the mouth of the Connecticut River (Figure 2.6 (3)). Both gages are of the bubbler type and can record a 35 foot tidal range. In Old Saybrook, the gage is mounted off the Saybrook Breakwater, and a digital recorder (punched paper tape) is located in the Coast Guard's outer lighthouse. In Groton, the gage is mounted off a pier, and both a digital and analog recorder are located in a former Coast Guard building now owned by the University of Connecticut. Neither of these two gages is equipped with a Telemark unit for remote transmission of data. (36,37,38)

Records for the Poquonock River gage are available since January 1973, and for the Connecticut River gage since October 1979 (data available from June 1976 to February 1978 at a different location 0.6 miles north). The USGS collects, maintains and publishes data from these two stations in the same manner it does for the gage at Stamford Harbor. (35,36)

NOS Subordinate Stations. The long-term records of the NOS stations at New London, Bridgeport and Willets Point serve as reference marks for other locations. At 38 "subordinate" locations along the Connecticut coast (and 7 on the north shore of Long Island), NOS installed temporary tide gages and made simultaneous tide observations at the temporary station and either the New London or Bridgeport permanent station (Table 2.2). The approximate time and height of tides at each of these locations can be determined by using the relationships developed by NOS. Included in the NOS annual tide tables is a tide table that provides the time and height relationship of each subordinate stations to a primary station. (4,7,30,41)

2.5 COASTAL FLOODING IN CONNECTICUT

Flooding of coastal areas in Connecticut may result from both coastal and inland storms. Storms that deposit excessive rainfall over upland watersheds may cause rivers and streams to overflow in lowlying coastal areas. This type of flooding may be particularly serious when the peak flood runoff coincides with high tide or storm surge that slows the discharge of floodwaters into Long Island Sound, causing additional backup and overflow of floodwaters. Lowlying areas right along the coast may be flooded directly by storm surge and wave action.

NO.	PLACE	POSITION Lat.	POSITION Long.	DIFFERENCES Time High water	DIFFERENCES Time Low water	DIFFERENCES Height High water	DIFFERENCES Height Low water	RANGES Mean	RANGES Spring	Mean Tide Level
		° ′ N	° ′ W.	h. m.	h. m.	ft	ft	ft	ft	ft
	CONNECTICUT, Long Island Sound			on NEW LONDON						
1187	Stonington, Fishers Island Sound	41 20	71 54	-0 32	-0 41	+0.1	0.0	2.7	3.2	1.3
1189	Noank, Mystic River entrance	41 19	71 59	-0 22	-0 08	-0.3	0.0	2.3	2.7	1.2
1191	West Harbor, Fishers Island, N. Y.	41 16	72 00	0 00	-0 06	-0.1	0.0	2.5	3.0	1.2
1192	Silver Eel Pond, Fishers Island, N. Y.	41 15	72 02	-0 16	-0 04	-0.3	0.0	2.3	2.7	1.1
	Thames River									
1193	NEW LONDON, State Pier	41 22	72 06	Daily predictions				2.6	3.0	1.3
1195	Smith Cove entrance	41 24	72 06	0 00	+0 10	-0.1	0.0	2.5	3.0	1.2
1197	Norwich	41 31	72 05	+0 13	+0 25	+0.4	0.0	3.0	3.6	1.5
1199	Millstone Point	41 18	72 10	+0 09	+0 01	+0.1	0.0	2.7	3.2	1.3
	Connecticut River									
1200	Saybrook Jetty	41 16	72 21	+1 11	+0 45	+0.9	0.0	3.5	4.2	1.7
1201	Saybrook Point	41 17	72 21	+1 11	+0 53	+0.6	0.0	3.2	3.8	1.6
1202	Lyme, highway bridge	41 19	72 21	+1 25	+1 10	+0.5	0.0	3.1	3.7	1.5
1203	Essex	41 21	72 23	+1 39	+1 38	+0.4	0.0	3.0	3.6	1.5
	Connecticut River									
1204	Hadlyme <7>	41 25	72 26	+2 19	+2 23	+0.1	0.0	2.7	3.2	1.3
1205	East Haddam	41 27	72 28	+2 42	+2 53	+0.3	0.0	2.9	3.5	1.4
1206	Haddam <7>	41 29	72 30	+2 48	+3 08	-0.1	0.0	2.5	3.0	1.2
1207	Higganum Creek	41 30	72 33	+2 55	+3 25	0.0	0.0	2.6	3.1	1.3
1209	Portland <7>	41 34	72 38	+3 51	+4 28	-0.4	0.0	2.2	2.6	1.1
1211	Rocky Hill <7>	41 39	72 38	+4 44	+5 44	-0.6	0.0	2.0	2.4	1.0
1213	Hartford <7>	41 46	72 40	+5 30	+6 52	-0.7	0.0	1.9	2.3	1.0
				on BRIDGEPORT,						
1214	Westbrook, Duck Island Roads	41 16	72 28	-0 24	-0 32	-2.7	0.0	4.1	4.7	2.0
1215	Duck Island	41 15	72 29	-0 26	-0 35	-2.3	0.0	4.5	5.2	2.2
1217	Madison	41 16	72 36	-0 21	-0 30	-1.9	0.0	4.9	5.6	2.4
1219	Falkner Island	41 13	72 39	-0 14	-0 25	-1.4	0.0	5.4	6.2	2.7
1220	Sachem Head	41 15	72 42	-0 11	-0 15	-1.4	0.0	5.4	6.2	2.7
1221	Money Island	41 15	72 45	-0 12	-0 23	-1.2	0.0	5.6	6.4	2.8
1223	Branford Harbor	41 16	72 49	-0 08	-0 18	-0.9	0.0	5.9	6.8	2.9
1225	New Haven Harbor entrance	41 14	72 55	-0 09	-0 14	-0.6	0.0	6.2	7.1	3.1
1227	New Haven (city dock)	41 18	72 55	+0 01	-0 01	-0.8	0.0	6.0	6.9	3.0
1229	Milford Harbor	41 13	73 03	-0 08	-0 10	-0.2	0.0	6.6	7.6	3.3
1231	Stratford, Housatonic River	41 11	73 07	+0 26	+1 01	-1.3	0.0	5.5	6.3	2.7
1233	Shelton, Housatonic River	41 19	73 05	+1 35	+2 44	-1.8	0.0	5.0	5.8	2.5
1235	BRIDGEPORT	41 10	73 11	Daily predictions				6.8	7.7	3.4
1237	Black Rock Harbor entrance	41 09	73 13	-0 04	-0 03	+0.1	0.0	6.9	7.9	3.4
1239	Saugatuck River entrance	41 06	73 22	-0 02	+0 01	+0.2	0.0	7.0	8.0	3.5
1241	South Norwalk	41 06	73 25	+0 09	+0 15	+0.3	0.0	7.1	8.2	3.5
1243	Greens Ledge	41 03	73 27	-0 02	-0 01	+0.4	0.0	7.2	8.3	3.6
1245	Stamford	41 02	73 33	+0 03	+0 08	+0.4	0.0	7.2	8.3	3.6
1247	Cos Cob Harbor	41 01	73 36	+0 05	+0 11	+0.4	0.0	7.2	8.3	3.6
1249	Greenwich	41 01	73 37	+0 01	+0 01	+0.6	0.0	7.4	8.5	3.7
1251	Great Captain Island	40 59	73 37	0 00	+0 01	+0.5	0.0	7.3	8.4	3.6
	NEW YORK Long Island Sound, North Side			on WILLETS POINT,						
1253	Port Chester	41 00	73 40	-0 03	-0 14	+0.1	0.0	7.2	8.5	3.6
1254	Rye Beach	40 58	73 40	-0 22	-0 31	+0.1	0.0	7.2	8.4	3.6
1255	Mamaroneck	40 56	73 44	-0 02	-0 13	+0.2	0.0	7.3	8.6	3.6
1257	New Rochelle	40 54	73 47	-0 18	-0 19	+0.1	0.0	7.2	8.6	3.6
1259	Davids Island	40 53	73 46	+0 04	-0 09	+0.1	0.0	7.2	8.5	3.6
1261	City Island	40 51	73 47	+0 03	-0 05	+0.1	0.0	7.2	8.5	3.6
1263	Throgs Neck	40 48	73 48	+0 08	+0 12	-0.1	0.0	7.0	8.2	3.5

SOURCE: National Ocean Service. 1984. Tide Tables: 1985 High and Low Water Predictions, East Coast of North and South America, Including Greenland. NOAA, U.S. Dept. of Commerce.

TABLE 2.2: National Ocean Survey Subordinate Tide Gage Locations in Long Island Sound, Showing Tidal Differences and Other Constants

2.5.1 Hurricanes and Tropical Storms (Tropical Cyclones)

The term tropical cyclone applies to atmospheric systems which develop in the tropical and subtropical zones and have a counterclockwise rotation of winds (in the northern hemisphere), with the lowest barometric pressure located at the center of the vortex. To develop, they require surface water temperatures above about 26 C (79 F), and are maintained by energy from condensation of water vapor drawn from the warm ocean surface. Consequently, most tropical cyclones occur in August, September and October (the official tropical cyclone season is from June 1 through November 30). They dissipate quickly as they pass over land masses or cold water and are deprived of the warm, moist air that supplies energy.

Tropical cyclones range in diameter from 50 to more than 500 miles. Several categories of tropical cyclones are recognized according to their intensity and degree of organization:

(1) tropical disturbance (little or no rotary circulation at the surface and no strong winds);

(2) tropical depression (winds equal to or less than 38 mph);

(3) tropical storm (winds of 39 mph or more); and

(4) hurricane (winds of 75 mph or more).

Tropical storms and hurricanes are of major concern as causes of severe coastal flooding. Hurricanes are further divided into five categories (Saffir/Simpson Hurricane Scale) according to their central pressure and maximum sustained winds (Table 2.3).

In hurricanes, atmospheric pressure and wind speed increase rapidly with distance outward from the center, or eye, of the storm (not necessarily the geometric center) to a zone of maximum wind speed which may be anywhere from 4 to 60 nautical miles from the center. From the zone of maximum wind to the edge of the hurricane, pressure continues to increase, but wind speed decreases. The atmospheric pressure within the eye (central pressure index)

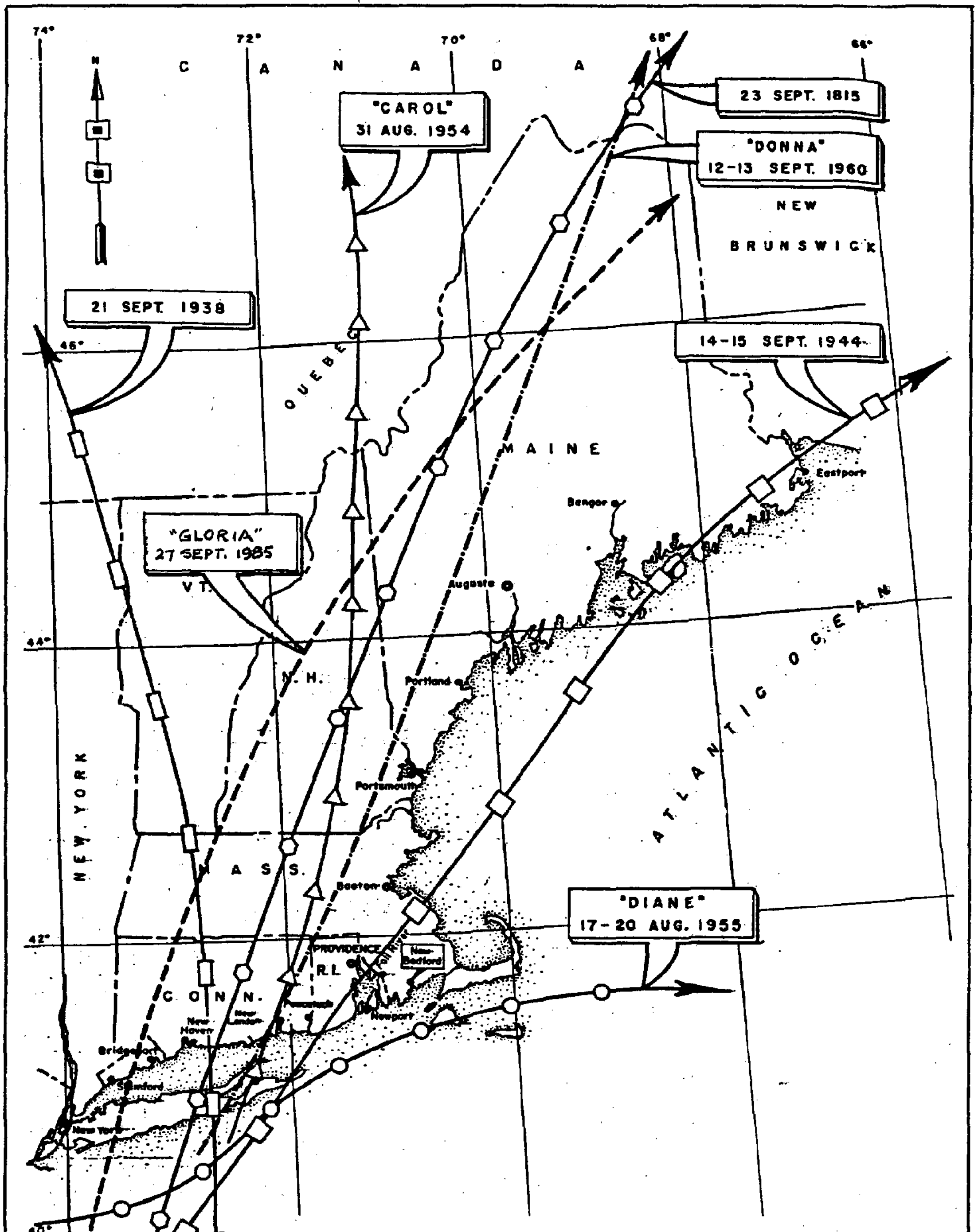
CATEGORY	CENTRAL PRESSURE (Inches Mercury)	WINDS (mph)
1	>28.94	74-95
2	28.50-28.93	96-110
3	27.89-28.49	111-130
4	27.18-27.88	131-155
5	<27.17	>155

TABLE 2.3: SAFFIRE/SIMPSON HURRICANE SCALE

is the best single index for estimating the surge potential of a hurricane. Hurricanes may also be characterized by the radius of maximum winds, which is an index of the size of the storm, and the speed of forward motion of the storm.

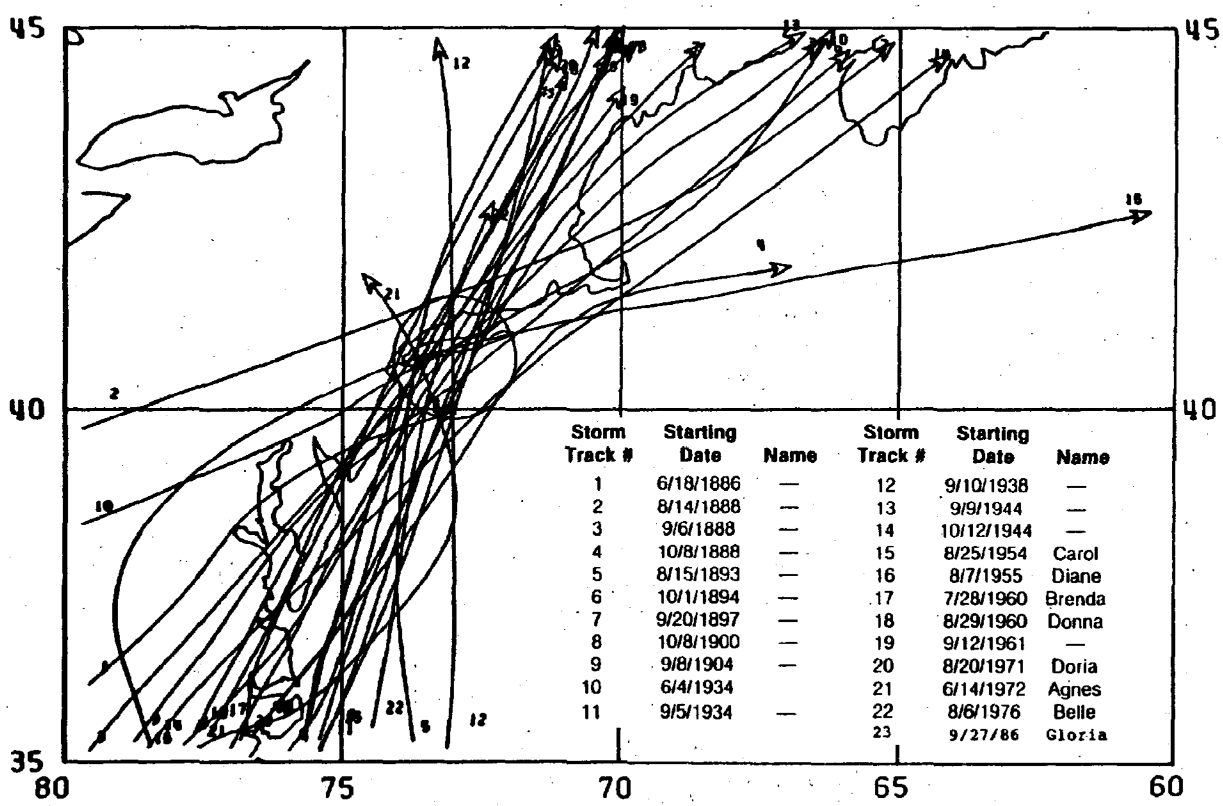
The path of an individual storm is determined by its point of origin, and by the relative position and strength of low and high pressure centers located in the westerly wind belt and over the Atlantic Ocean. From 1886-1985 nine hurricanes (including Hurricane Gloria in September 1985) have passed over or near Long Island Sound (50 mile radius of the center of Long Island). The tracks of six selected hurricanes are shown in Figure 2.12. During this same period, 15 tropical storms have hit the area. The tracks of all hurricanes and tropical storms are shown in Figure 2.13. Prediction of the path which a particular hurricane or tropical storm will take is very imprecise. (11,42,43)

Utilizing statistical data on the motion of tropical storms in the Atlantic area, Neumann and Pryslak (44) calculated the expected number of tropical storms and hurricanes per 100-year period impacting locations along the U.S. coastline. Figure 2.14 shows the grids that encompass the Connecticut coastline. The data in Figure 2.14 show that tropical storm occurrence in Grid 518, which includes the eastern portion of Long Island Sound, is greater than in Grid 517, which includes the western part of the Sound. Based on actual tropical storm occurrence and movement data, the expected number of tropical storms



SOURCE: Adapted from Corps of Engineers, New England Division. 1982. Regulations Manual, Stamford Hurricane Barrier, Stamford, CT. Corps of Engineers, Dept. of the Army.

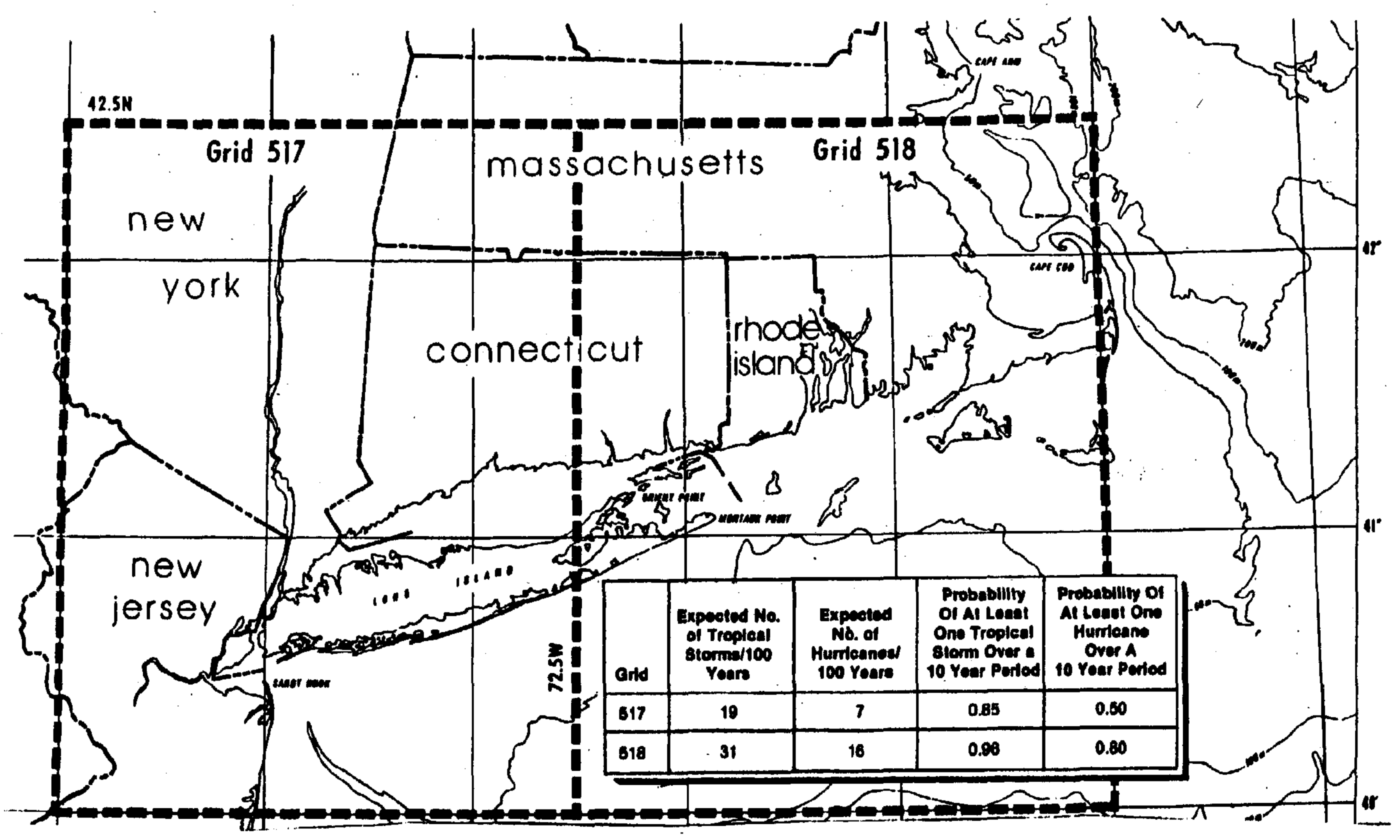
FIGURE 2.12: Tracks of Seven Selected Hurricanes Crossing or Approaching Long Island Sound



Storm Track #	Starting Date	Name	Storm Track #	Starting Date	Name
1	6/18/1886	—	12	9/10/1938	—
2	8/14/1888	—	13	9/9/1944	—
3	9/6/1888	—	14	10/12/1944	—
4	10/8/1888	—	15	8/25/1954	Carol
5	8/15/1893	—	16	8/7/1955	Diane
6	10/1/1894	—	17	7/28/1960	Brenda
7	9/20/1897	—	18	8/29/1960	Donna
8	10/8/1900	—	19	9/12/1961	—
9	9/8/1904	—	20	8/20/1971	Doria
10	6/4/1934		21	6/14/1972	Agnes
11	9/5/1934	—	22	8/6/1976	Belle
			23	9/27/86	Gloria

SOURCE: Adapted from Long Island Regional Planning Board. 1984. Hurricane Damage Mitigation Plan for the South Shore of Nassau and Suffolk Counties, New York. Long Island Regional Planning Board, Hauppauge, NY.

FIGURE 2.13: Tropical Storms and Hurricanes Passing Near Long Island Sound



Grid	Expected No. of Tropical Storms/100 Years	Expected No. of Hurricanes/ 100 Years	Probability Of At Least One Tropical Storm Over a 10 Year Period	Probability Of At Least One Hurricane Over A 10 Year Period
517	19	7	0.85	0.50
518	31	16	0.96	0.80

SOURCE: Neumann, C.J. and M.J. Pryslak. 1981. Frequency and Motion of Atlantic Tropical Cyclones. NOAA Technical Report NWS 26. National Hurricane Center, Coral Gables, FL.

FIGURE 2.14: Expected Number of Tropical Storms and Hurricanes per 100 Years Impacting the Long Island Sound Region

entering Grid 518 per 100 years is 31; 16 of these storms would be hurricanes. In Grid 517, 19 tropical storms per 100 years would be expected, of which seven would be hurricanes. The probability that at least one tropical storm will impact the Connecticut coastline over the next 10 years ranges from 0.85 to 0.96. The probabilities that at least one hurricane will impact this area over the next 10 years are slightly less, ranging from 0.50 to 0.80. (45)

Since hurricane winds move in a counterclockwise spiral, the winds in the right quadrants of this spiral are more or less parallel with, and reinforced by, the translational (forward) movement of the storm. This reinforcement can be of considerable magnitude, as hurricanes have travelled at forward speeds of over 50 knots. The winds to the left of the storm track are weaker than those to the right, because the winds blow in directions opposite to the translational movement of the storm. Consequently, winds and storm surge are normally at a maximum in the northeast quadrant of hurricanes. (11,42,43)

South-facing coasts, like Connecticut's, that are aligned perpendicular to most storm tracks, receive the full impact of the reinforced winds and wave set-up. However, Long Island Sound and Connecticut are somewhat protected by Long Island, which blocks ocean-generated waves from reaching most of the Connecticut coast, and which may cause a hurricane to weaken as it passes over the colder land mass. In general, fast moving hurricanes have peak storm surges that are higher than slower moving storms. However, slower moving storms can cause a higher surge in estuarine areas, such as Long Island Sound, because there is more time for water to flow into the Sound. (11,45)

Figures B.1 and B.2 (Appendix B) display data on actual storm surge levels recorded during the 1938 and 1954 hurricanes, along with projected storm surge profiles for 100, 50 and 10-year frequencies (6,46). The 100-year flood profile shows the highest flood level in western Connecticut (12.2 feet NGVD), lowering to 10 feet by Stratford. From Stratford east the level rises to about 10.7 feet at East Haven, followed by a gradual decrease to about 10.0 feet at Waterford. At New London the level is 10.0 feet NGVD. To the east of New London the flood level increases from about 10.0 feet to 10.8 feet at Stonington.

Storm surge is seen to increase dramatically within the Thames River Estuary. According to the COE 1980 (12) study, storm surge increased from

9.5 feet to 14.3 feet NGVD at the 100-year level as the distance from the mouth of the Thames increased. The 1938 hurricane surge ranged from 9.8 feet at New London up to 15.2 feet in Norwich. Figure 2.15 shows tidal surges compared to the predicted normal tide levels at Stamford Harbor for the 1938, 1944 and 1954 hurricanes. (47)

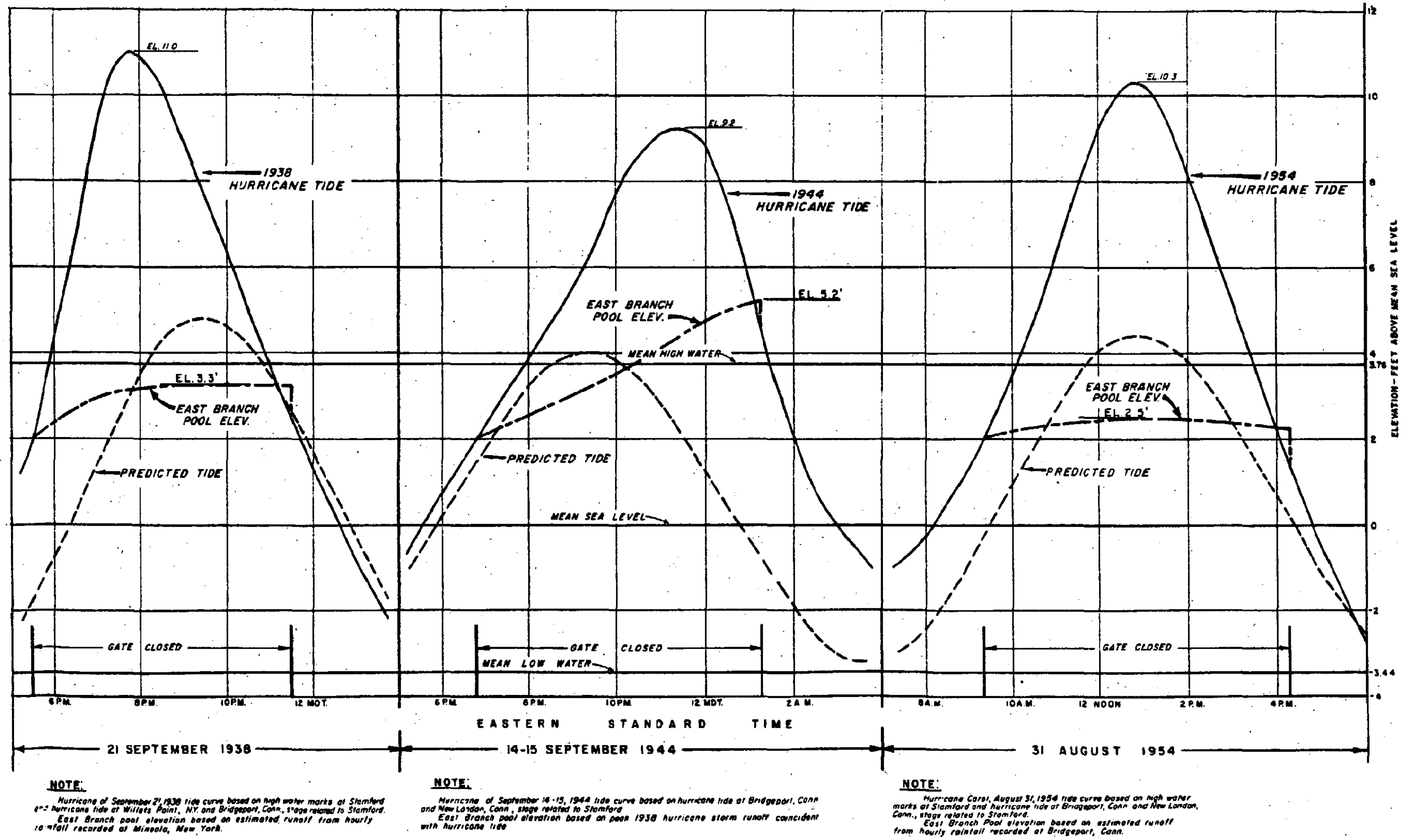
2.5.2 Extratropical Storms

Extratropical storms are weather systems that develop in mid-latitudes in the fall, winter and spring (most commonly November through April), in response to the interaction of warm and cool air masses along a weather front. They occur much more frequently than tropical cyclones, and may be more than 1000 miles in diameter -- two or three times the size of a tropical cyclone. Extratropical storms also form a counterclockwise spiral directed toward a center of low barometric pressure, but the maximum winds are of lower velocity than tropical cyclone winds. Some gusts of hurricane velocity may occur with extratropical storms.

Extratropical storms that occur along the northern part of the east coast of the U.S. accompanied by strong winds blowing from the northeast quadrant are called northeasters. Northeasters may stall off the southeast coast of New England and produce high tides that persist for several days. An example of this is the storm of October 1955 when high tides continued from 14-16 October. (11,45,48)

A study of northeasters affecting the Atlantic coastal margin of the United States during the period 1921-1962 (48) found that during the 42 year period of record, 34 extratropical storm events occurred that resulted in water-related damage, i.e., damage due to wave action and tidal flooding. The recurrence interval of such storm events is 1.24 years. Stated in another way, a storm of this nature has an 81% chance of occurrence in a given year, based on the observed data. (45)

Wind directions from extratropical storms at a particular area depend on the relative position of the storm track. When a storm center passes to



SOURCE: New England Division. 1982. Regulation Manual, Stamford Hurricane Barrier, Stamford, Connecticut. U.S. Corps of Engineers, Waltham, MA.

FIGURE 2.15: Selected Storm Surges at Stamford Harbor, Stamford, Connecticut

the west of Connecticut, winds blow initially from the east or southeast. As storm movement progresses, the winds shift to south and then west. This type of storm results in onshore winds, leading to increased wave height and wind set up. If, on the other hand, the storm center passes to the east of Connecticut, the initial winds will blow from the northeast. Later the winds will veer to the north and northwest. This type of storm produces offshore winds and a smaller storm surge due to reduced effects of waves and wind set up. (45)

The effect of northeasters on shoreline areas often depends on their speed of forward movement. If the storm progresses rapidly, variable wind directions over a given fetch length prevent the buildup of large storm waves. However, if storm progress is delayed by ridges of high pressure, winds from a particular direction have time enough to act on a given wave group, to produce waves of maximum height for a specific wind velocity and fetch. Prolonged wave action during successive high tides can lead to erosion and damage to shoreline development. (45)

2.5.3 Mapping of Coastal Floodplains

Coastal areas (as well as riverine floodplains) subject to flooding have been identified on Flood Insurance Rate Maps (FIRMs) prepared by FEMA and its contractors. These FIRMs delineate areas with a one percent or greater chance of being flooded each year (commonly referred to as the one-percent flood, 100-year flood and base flood). The 1938 hurricane produced flooding approximately equal to the one-percent flood over much of the Connecticut coastline (see Figure B.1).

Coastal floodplains subject to damaging wave action (waves three feet or higher) are designated on FIRMs as V-zones[3]. Areas subject to flooding from storm surge, but with no wave action or waves less than three feet, are

---

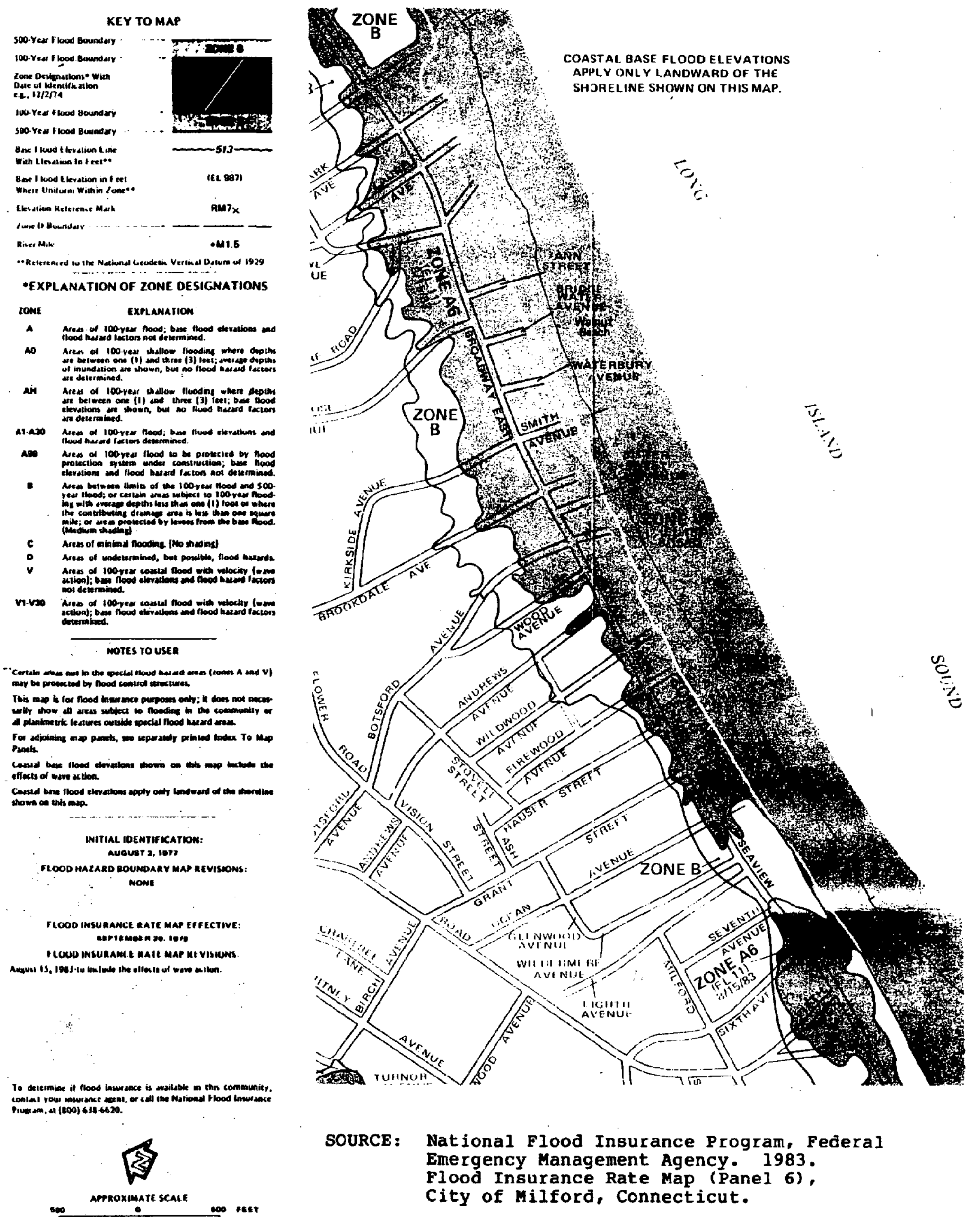
[3] A three-foot high wave was selected for determination of the V-zone based on data compiled by the COE, which indicated that a three-foot wave was capable of causing structural damage. (51)

designated as A-zones. (49,50,51) Figure 2.16 shows a portion of the coastal floodplain in the Town of Milford as delineated on a recently adopted FIRM.

FIRMs provide a good basis for designating areas subject to floodplain regulations and flood-related building code requirements. However, because the different flood zones delineated on FIRMs have not been correlated with particular storm characteristics, these maps cannot be used to acurately estimate which areas will be flooded during a developing hurricane or other storm. Nevertheless, they provide the only information presently available on which to base evacuation notices in coastal areas.

2.5.4 Flood Damages

Five hurricanes (including Gloria in 1985) and several northeasters have caused damaging coastal flooding in this century. The hurricanes of 1938, 1944 and 1954 caused the most damage. Unfortunately, very limited information is available on the dollar amount of damages caused by these and other storms, particularly the smaller storms. In 1976 the COE estimated that, in 1975 dollars, a recurrence of the 1938 hurricane would cost $111,500,000 in losses from tidal flooding, and a recurrence of the 1954 hurricane would cause losses of $72,000,000. (12) No updated estimate has been made since that time. However, it is likely that due to increased development along the coast, the losses in 1985 would be more than double the amount estimated in 1976. As an indication of the amount of property at risk, Table 2.4 lists the number of structures located in V-Zones for each of the coastal towns. (52)



SOURCE: National Flood Insurance Program, Federal Emergency Management Agency. 1983. Flood Insurance Rate Map (Panel 6), City of Milford, Connecticut.

FIGURE 2.16: FEMA Flood Insurance Rate Map for Section of Milford, Connecticut

	Residential	Commercial/Industrial	Total
Greenwich	207	1	208
Stamford	10	0	10
Darien	125	1	126
Norwalk	145	2	147
Westport	275	0	275
Fairfield	98	2	100
Bridgeport	24	3	27
Stratford	229	16	245
Milford	615	8	623
West Haven	240	6	246
New Haven	50	1	51
East Haven	349	4	353
Branford	388	3	391
Guilford	174	0	174
Madison	270	5	275
Clinton	95	0	95
Westbrook	126	0	126
Old Saybrook	234	1	235
Old Lyme	131	1	132
East Lyme	4	1	5
Waterford	12	0	12
New London	35	13	48
Groton	16	6	22
Stonington	15	0	15
TOTAL	3,867	74	3,937

SOURCE: Rummel, Cynthia J., and G.J. Hudak. 1984-1985. Flood Vulnerability Assessment (for 24 coastal Connecticut municipalities). Natural Resources Center, Department of Environmental Protection, Hartford, CT.

TABLE 2.4: Structures Located in V-Zones

3.0 FLOOD FORECASTS AND WARNINGS IN CONNECTICUT

The procedures used by federal, state and local governments to prepare and disseminate coastal flood forecasts and warnings must be understood in order to evaluate the feasibility of developing an improved flood warning system.

3.1 RIVERINE FLOOD FORECASTS AND WARNINGS

Although a coastal flood monitoring network and warning system would not be comparable in all respects to an automated riverine flood forecasting and warning system, a coastal system would share many similarities. It was the development of an automated riverine flood warning system for Connecticut that led State officials to consider the possibility of also establishing a compatible coastal flood monitoring network and warning system. (53)

3.1.1 National Weather Service ALERT System

For years the NWS has maintained cooperative flood warning systems in many communities throughout the U.S. These cooperative systems rely upon a network of community volunteers to make regular observations of rainfall and/or river levels and to telephone their observations to the appropriate NWS office. The NWS uses the data gathered by the volunteers, along with its own data on soil moisture conditions and precipitation forecasts, to run a hydrological model of the river basin and predict the time and level of flooding. While very effective in some communities, these programs have inherent limitations. Most notably, observers are not always available to collect and report data on precipitation and river levels, particularly during the night and at remote locations.

In recognition of these limitiations, in the late 1970's the NWS began developing an automated flood warning system. The automated system was designed to take advantage of technological advances that permit real-time collection and transmittal of meteorological and hydrological data from remote locations to populated areas with people and property at risk.

The resulting system was called ALERT (Automated Local Evaluation in Real Time). The ALERT system does not rely upon volunteer observers; it is entirely automated. The major components of the ALERT system are: precipitation gages, river gages, radio transmitters, radio receivers, data encoders and decoders, a microcomputer, and specially designed software to process the data. Remote rain gages automatically collect data on amounts and rates of rainfall and transmit this information via VHF radio to a base station. Similarily, stream gage stations transmit data on the rise in river levels. Generally, data collection and transmittal from remote locations is battery powered. Because the system is designed for "event reporting" (data transmitted only when there is a predetermined amount of rainfall or change in stream level), batteries can last a year or more without recharging.

When predetermined critical precipitation and/or stream level values are reached, an alarm is triggered at the base stations and personnel are placed on alert to monitor the situation closely. Using the rainfall and river rise information, combined with precipitation forecasts and a hydrologic model of the stream, NWS personnel are able to accurately forecast floods and provide downstream officials and residents with increased warning time. Since the information is also received at a local base station, local officials can, if necessary, initiate flood warnings without waiting for a forecast from the NWS. The increase in warning time afforded by the automated system is often sufficient to permit emergency actions which can save lives and greatly reduce property losses.

ALERT systems were initially used in the western US where sudden rainstorms in the remote, upper portions of watersheds can cause flash floods in lower portions of the watershed where no rain may have fallen. ALERT systems have now been successfully installed in more than two dozen locations throughout the U.S., and many more are now under development. The original ALERT system was developed by the NWS, but several private firms have now developed similar systems. ALERT type systems have found wide acceptance on large and remote river basins in countries other than the U.S. (54,55,56,57,58,59,60,61,62)

3.1.2 Connecticut Automated Flood Warning System

In 1982 Connecticut and NWS officials began examining the possibility of a statewide automated flood warning system for small watersheds subject to flash floods. An interagency Committee on Automated Flood Warning (CAFW) was established to oversee development of the statewide system. Particularly important to CAFW was the technical assistance provided by the NWS and technical and financial assistance from the Soil Conservation Service (SCS).

A statewide system was designed in 1983 and called ASERT (Automated State Evaluation in Real Time). ASERT is intended to be operated in cooperation with local communities, and the combined system is sometimes referred to as ASERT/ALERT. The initial phase of the ASERT system is now being installed and consists of 20 automated rain gages, 6 weather stations (including precipitation gages), 6 radio signal repeaters, and 2 base stations. Each base station includes a radio receiver, data decoder, microcomputer, ALERT software, and an uninterruptable power supply backup. The base stations are located at the Northeast River Forecast Center (NERFC) in Bloomfield and the DEP offices (Water Resources Unit) in Hartford.

Concurrently with installation of the ASERT system, community ALERT systems are being installed on a pilot basis in the City of Norwich (Yantic River basin) and the Town of Southington (Quinnipiac River basin). Each ALERT system includes an automated river gage and a base station. The City of Stamford has also installed its own ALERT system (63).

The initial ASERT/ALERT system should be operational in 1986, and the State expects the system to be expanded into other river basins as local communities recognize the benefits of the program. CAFW has prepared a master plan that projects an additional 85 precipitation gages, 24 repeaters, 40 river gages, and 28 base stations will be added to the system over the next 10 years. This system design may change as CAFW continues its work and experience with the initial installations is obtained. Important aspects of the ASERT system that are still evolving include procedures for archiving data and providing maintenance.

The CAFW master plan also includes a coastal component. The purpose of this present study is to design the coastal monitoring network and evaluate the feasibility of a coastal warning system as part of the ASERT/ALERT system. Specifications for the ASERT components that may be used by the coastal network are provided in Appendix A. (53,64,65,66,67)

3.2 COASTAL FORECASTS AND WARNINGS FOR CONNECTICUT AND LIS

Currently, all official weather forecasts (including storm surge and wave heights) and coastal flood warnings for Connecticut and Long Island Sound are provided by the NWS. The procedures used by NWS for preparing these forecasts and warnings and then disseminating them to other units of government and to the public are described in the following sections.

3.2.1 NWS Procedures

Different NWS offices are involved with forecasts and warnings depending upon the type of weather system and flood component involved.
Forecasts and warnings for coastal Connecticut can be complicated because the Connecticut shoreline forms the border between the areas served by the Boston Weather Service Forecast Office (WSFO) and the New York WSFO. (32,68,69,75)

MARINE WEATHER FORECASTS AND WARNINGS The New York WSFO is responsible for marine forecasts and warnings for LIS, to Watch Hill, Rhode Island and Montauk Point on Long Island[1]. The Bridgeport WSO prepares marine bulletins for Fairfield, New Haven and Middlesex counties using the New York WSFO forecast supplemented with information on local conditions. The Hartford WSO prepares similar bulletins for New London County. Marine weather bulletins are routinely issued over NOAA VHF-FM Weather Radio (162.400 MHz, Meriden; 162.475 MHz, Hartford; and 162.55 MHz, New London and New York). These same weather bulletins are transmitted

[1] The Boston WSFO is responsible for forecasts and warnings for the New England area, including all land areas of Connecticut. Wind forecasts by Boston WSFO for Connecticut and by New York WSFO for LIS sometimes differ, requiring consultation among the New York and Boston WSFOs and the Bridgeport and Hartford WSOs. (32,68,75)

over the NWS teletype to selected government agencies and print and broadcast media. In addition to NWS teletype and NOAA Weather Radio, warnings of severe weather conditions, including flood watches and warnings, are issued over the National Warning System (NAWAS).

NWS offices at Bridgeport, and New York can be telephoned to receive the latest marine forecast or warning. Every six hours, the Bridgeport WSO prepares an updated tape of marine forecasts and warnings, including a report on local weather conditions at the Bridgeport WSO. If the Bridgeport WSO observes local conditions significantly different from the marine forecast issued by New York WSFO, it contacts the New York WSFO. The Coast Guard stations at New Haven and New London also broadcast NWS marine forecasts and warnings over its radio frequencies, and maintain day and night visual warnings for mariners at several locations along the Connecticut coast. (15,32,68,69,70,76)

<u>WAVE HEIGHT FORECASTS</u> Forecasts of wave heights are developed by the New York WSFO, which has forecast responsibility from Watch Hill, RI to Manasquan, NJ, including Long Island Sound west of Watch Hill. These forecasts are made routinely every six hours for use in the LIS marine forecast. The forecasts of wind waves are prepared using information on present wind speed, wind duration, and fetch length, or forecast wind speed. According to information supplied by the New York WSFO, it uses at least two sets of wind wave forecast charts, both of which were developed for predicting waves in open seas[2]. In applying these procedures to wave forecasts in LIS, the meteorologists make adjustments based on their experience. Information on wind speed which is used in the wave forecasts is obtained from meteorological instruments along the Connecticut shore (Bridgeport, New Haven airport, Groton airport), at several locations on Long Island (La Guardia airport, Islip airport, Farmingdale airport, Suffolk airport, Plum Island, and Montauk Point), and from reports of ships at sea. The wave height forecasts are intended for mariners and reflect average wave conditions in open coastal waters. They are not intended to indicate breaking wave heights in coastal areas. (20,32,69,74,145)

---

[2]See Section 4.1.2 and Appendix B for a discussion of wave forecasting/ hindcasting models.

EXTRATROPICAL STORMS Weather forecasts for extratropical storms are prepared by the New York WSFO for LIS and by the Boston WSFO for inland Connecticut. Both the New York and Boston WSFOs use data and forecast guidance from the NWS National Meteorological Center (NMC) in Silver Springs, Maryland. (15,71,72,75)

Using an automated statistical model, the NMC prepares storm surge forecasts twice daily, projected for a 48-hour period. This information is provided to the regional WSFO at New York City as guidance (Figure 3.1). The New York WSFO may modify the forecast, if needed, based on observations of local conditions and using a manual version of the statistical storm surge model[3]. The New York WSFO receives reports of actual storm surge conditions from the Bridgeport WSO (every 6 hours) and from four stations in New York Harbor (every 6 minutes), which may be used in revising storm surge forecasts. (15,71,73)

There is no established procedure for verifying the accuracy of storm surge or wave forecasts. There is no instrumentation to record actual wave heights and no systematic observations of wave heights are made.(20,32)

HURRICANES The National Hurricane Center (NHC) in Coral Gables, Florida issues all forecasts and storm warnings for hurricanes, including storm surge forecasts generated by a numerical model called SLOSH (Sea, Lake and Overland Surges from Hurricanes). A separate wave height forecast is not prepared for hurricanes since the SLOSH[4] model indirectly incorporates waves into its storm surge prediction. NWS Regional WSFOs and local WSOs do not modify the NHC forecasts and warnings, although they may supplement them with up-to-date reports on local conditions, including wave heights, and provide additional warnings for particular geographic areas. Local weather conditions are provided to the NHC over a Hurricane Hotline by NWS offices in the affected areas, and used by the NHC is developing its hurricane forecast. (20,32,68,69,72)

---

[3]See Section 4.1.1 and Appendix B for a discussion of the NWS storm surge models for extratropical storms.

[4]See Section 4.1 and Appendix B for more complete descriptions of the SLOSH model.

FZUS3 KWBC 021200
STORM SURGE FCST FEET INVALID FOR TROPICAL STORMS

	12Z	18Z	00Z	06Z	12Z	18Z	00Z	06Z	12Z
PWM	0.1	0.4	0.5	0.7	0.7	0.9	0.8	0.9	0.7
BOS	0.1	0.2	0.3	0.4	0.4	0.5	0.4	0.6	0.3
NWP	0.8	1.0	1.1	1.2	1.2	1.3	1.1	1.1	0.9
SFD	1.0	1.1	1.2	1.2	0.9	0.7	0.6	0.1	0.0
LGA	1.0	1.0	1.0	1.3	1.2	1.0	1.0	0.8	0.7
NYC	1.2	1.3	1.4	1.4	1.3	1.2	1.0	0.9	0.7
ACY	0.8	0.9	1.0	0.9	0.9	0.9	0.8	0.8	0.7
BWH	1.1	1.1	1.2	1.0	0.9	0.9	0.7	0.7	0.6
BAL	2.4	2.5	2.6	2.8	2.8	2.6	2.4	2.0	1.9
ORF	0.9	0.8	0.9	0.8	0.8	0.8	0.7	0.6	0.9

PWM	Portland, Maine
BOS	Boston, Massachusetts
NWP	Newport, Rhode Island
SFD	Stamford, Connecticut
LGA	Willets Point, New York
NYC	New York, New York
ACY	Atlantic City, New Jersey
BWH	Breakwater Harbor, Delaware
BAL	Baltimore, Maryland
ORF	Hampton Roads, Virginia

(Note: Forecast time in 24 hour time.)

SOURCE: Pore, N.A., et. al. 1974. Forecasting Extratropical Storm Surges for the Northeast Coast of the U.S. NOAA Technical Memorandum NWS TDL-50. Washington, D.C.

FIGURE 3.1: Sample Storm Surge Forecast Guidance: Teletype Message to Weather Service Forecast Offices

Hurricane forecasts are updated by the NHC every six hours. Forecast preparation is initiated at 2 am, 8 am, 2 pm, and 8 pm EDT. When Hurricane Watches or Warnings[5] are not in effect, Public Advisories based on these forecasts are issued at 6 am, Noon, 6 pm, and 10:30 pm EDT[6]. Once the NHC issues a Watch or Warning for a particular area, Public Advisories are issued every three hours, and the 6 am, Noon, 6 pm and Midnight EDT advisories are based on the new forecasts.

Public Advisories include: an updated report on the position and track of the hurricane, forecast position, barometric pressure at the center, maximum sustained winds, wind gusts, areas subject to a Hurricane Watch or Warning, the predicted wind speeds and storm surge expected in those areas, and the probability of the hurricane reaching landfall at specific locations. Forecast positions are given for 12, 24, 36, 48, and 72 hours beyond the time the forecast is made.

Beginning with the 1983 hurricane season, the NHC began including in the Advisory the probability of the hurricane reaching landfall at specific locations. Probabilities are defined as the chance in percent that the center of the storm will pass within approximately 65 miles of a stated location. Probabilities are issued in tabular form, as shown in Figure 3.2. (77)

As was shown clearly during Hurricane Gloria, the NHC, as well as regional and local NWS offices, provide close coordination with local T.V. and radio stations serving areas within the projected track of a hurricane.

TROPICAL STORMS The NHC also prepares forecasts and warnings for tropical storms, and uses the SLOSH model to predict storm surges generated by tropical storms. As with hurricanes, no separate wave height is predicted. The New York WSFO may modify the tropical storm forecast and warning for LIS based

---

[5] A Hurricane Watch is issued for a coastal area when there is a threat of hurricane conditions within 24-36 hours. A Hurricane Warning is issued when hurricane conditions are expectd in a specified coastal area in 24 hours or less. (77)

[6] Except for the 10:30 pm advisory, the forecast preparation begins four hours before the advisory time. The 10:30 pm advisory is issued earlier in order that it may be available for the evening television news broadcast. (77)

MIATCPAT3
TTAA00 KNHC 262136
BULLETIN
HURRICANE GLORIA ADVISORY NUMBER 40
NATIONAL WEATHER SERVICE MIAMI FL
6 PM EDT THU SEP 26 1985

UPGRADE GALE WARNINGS TO HURRICANE WARNINGS NORTH OF CAPE HENRY TO PLYMOUTH MASSACHUSETTS INCLUDING CAPE COD. A HURRICANE WATCH IS IN EFFECT NORTH OF PLYMOUTH THROUGH EASTPORT MAINE.

HURRICANE WARNINGS ARE NOW IN EFFECT FROM LITTLE RIVER INLET TO PLYMOUTH MASSACHUSETTS. ALL WARNINGS HAVE BEEN DISCONTINUED SOUTH OF LITTLE RIVER INLET.

GLORIA IS MOVING TOWARDS THE NORTH 20 MPH AND IS EXPECTED TO CONTINUE NORTHWARD AND ACCELERATE ITS FORWARD MOTION TONIGHT.

THE EFFECT OF GLORIA THROUGHOUT THE WARNING AREA CRITICALLY DEPENDS UPON ITS PRECISE TRACK. IF THE CENTER OF THE HURRICANE REMAINS INLAND AFTER MOVING OVER EASTERN NORTH CAROLINA...ONLY GALES WILL BE EXPERIENCED NORTHWARD TO NEW ENGLAND. IF GLORIA SKIRTS THE COAST ...HURRICANE CONDITIONS WILL BE EXPERIENCED IN THE HURRICANE WARNING AREA. IF THE CENTER OF THE HURRICANE REMAINS OFFSHORE ALONG THE MID ATLANTIC COAST...ONLY GALES WOULD BE EXPERIENCED ALONG THAT COAST AND A MORE SERIOUS HURRICANE COULD AFFECT LONG ISLAND AND NEW ENGLAND. *HURRICANE FORECASTING SKILLS ARE NOT SUFFICIENT TO PREDICT* WHICH OF THESE POSSIBILITIES WILL OCCUR. THEREFORE...THE COURSE OF LEAST REGRET IS TO EXTEND HURRICANE WARNINGS NORTHWARD TO MASSACHUSETTS.

TIDES OF 8 TO 12 FEET ABOVE NORMAL WILL OCCUR NEAR AND TO THE RIGHT OF WHERE THE CENTER CROSSES THE COAST AND RANGE UP TO 6 FEET ABOVE NORMAL ON THE OUTER BANKS. DETAILS ON ACTIONS TO BE TAKEN ARE INCLUDED IN STATEMENTS BEING ISSUED BY NATIONAL WEATHER SERVICE OFFICES AND LOCAL GOVERNMENT OFFICIALS. EVACUATION FROM OFFSHORE ISLANDS SHOULD BE NEARING COMPLETION OVER EASTERN NORTH CAROLINA.

AT 6 PM EDT...2200Z...THE CENTER OF GLORIA WAS NEAR LATITUDE 32.6 NORTH LONGITUDE 76.4 WEST. THIS POSITION IS 190 MILES SOUTH OF CAPE HATTERAS NORTH CAROLINA.

A NOAA PLANE REPORTS THE WINDS ARE STILL 130 MPH AND THE CENTRAL PRESSURE IS 942 MILLIBARS...27.82 INCHES.

GALE FORCE WINDS EXTEND 200 MILES TO THE NORTH AND 150 MILES TO THE SOUTH OF THE CENTER.

SMALL CRAFT NORTH OF PLYMOUTH THROUGH MAINE SHOULD NOT VENTURE FAR FROM PORT.

REPEATING THE 6 PM EDT POSITION...32.6N...76.4W.

THE NEXT ADVISORY WILL BE ISSUED BY THE NATIONAL HURRICANE CENTER AT 9 PM EDT.

FRANK

ADVISORY NUMBER 40 HURRICANE GLORIA PROBABILITIES
FOR GUIDANCE IN HURRICANE PROTECTION PLANNING
BY GOVERNMENT AND DISASTER OFFICIALS

CHANCES OF CENTER OF GLORIA PASSING WITHIN 65 MILES OF LISTED LOCATIONS THROUGH 2 PM EDT SUN SEP 29 1985

CHANCES EXPRESSED IN PER CENT...TIMES EDT

COASTAL LOCATIONS	THRU 2 PM FRI	ADDITIONAL PROBABILITIES 2 PM FRI THRU 2 AM SAT	2 AM SAT THRU 2 PM SAT	2 PM SAT THRU 2 PM SUN	TOTAL THRU 2 PM SUN
WILMINGTON NC	31	X	X	X	31
MOREHEAD CITY NC	82	X	X	X	82
CAPE HATTERAS NC	78	X	X	X	78
NORFOLK VA	66	X	X	X	66
OCEAN CITY MD	50	1	X	X	51
ATLANTIC CITY NJ	39	4	X	X	43
NEW YORK CITY NY	23	14	X	X	37
MONTAUK POINT NY	6	18	X	X	24
PROVIDENCE RI	3	19	X	X	22
NANTUCKET MA	1	9	1	X	11
HYANNIS MA	1	13	X	X	14
BOSTON MA	2	20	X	X	22
PORTLAND ME	X	20	1	X	21
BAR HARBOR ME	X	11	3	X	14
EASTPORT ME	X	6	5	X	11
ST JOHN NB	X	4	4	1	9
MONCTON NB	X	2	5	1	8
YARMOUTH NS	X	3	2	X	5
HALIFAX NS	X	1	1	X	2
SYDNEY NS	X	X	1	1	2
EDDY POINT NS	X	X	1	1	2
PTX BASQUES NFLD	X	X	2	3	5
BURGEO NFLD	X	X	1	2	3

X MEANS LESS THAN ONE PERCENT

SOURCE: Bridgeport Weather Service Office, Stratford, CT.

FIGURE 3.2: Forecast for Hurricane Gloria, Showing Probabilities of Landfall

on local conditions, and both the New York WSFO and the Bridgeport and Hartford WSOs will supplement the forecast and warning with a report on local conditions. (20,68,69)

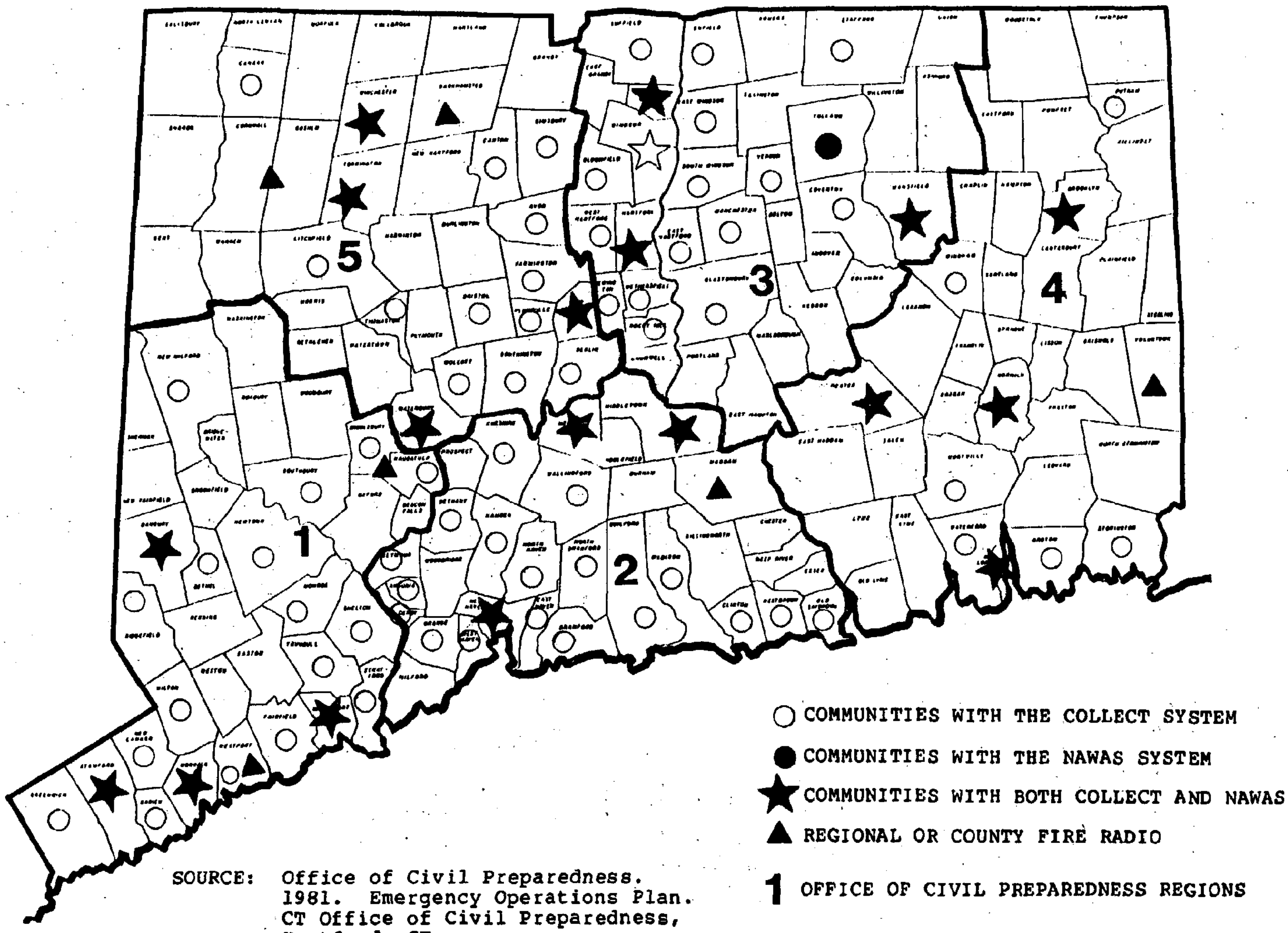
3.2.2 State of Connecticut Procedures

Offices of two Connecticut State agencies, identified as the State Warning Points, are responsible for receiving and disseminating emergency warnings. The primary State Warning Point is located in the Communication Division, Connecticut State Police (CSP), in Hartford. This location is manned continuously by full-time civilian radio dispatchers. The alternate State Warning Point is located at the Connecticut Office of Civil Preparedness (OCP) in Hartford. This office is manned during normal working days from 8:00 am to 4:00 pm. The OCP handles warning messages during working hours only. After hours, the CSP initiate warning activities.

Both Connecticut State Warning Points receive their information via NAWAS, NWS Teletype, and NOAA VHF radio. Upon receipt of a weather watch or warning, the State Warning Point activates the state NAWAS and COLLECT (Connecticut On-Line Law Enforcement Communications Teleprocessing) systems to distribute the warnings to each regional OCP office and appropriate officials in each municipality. Towns not equipped with either NAWAS or COLLECT systems (Figure 3.3) must be reached through the fanout system (Figure 3.4). Connecticut State Police Troups located in coastal areas may assist local officials in observing flood conditions, alerting residents, and taking other actions, such as blocking flooded roadways. (78,79,80,81,82,83)

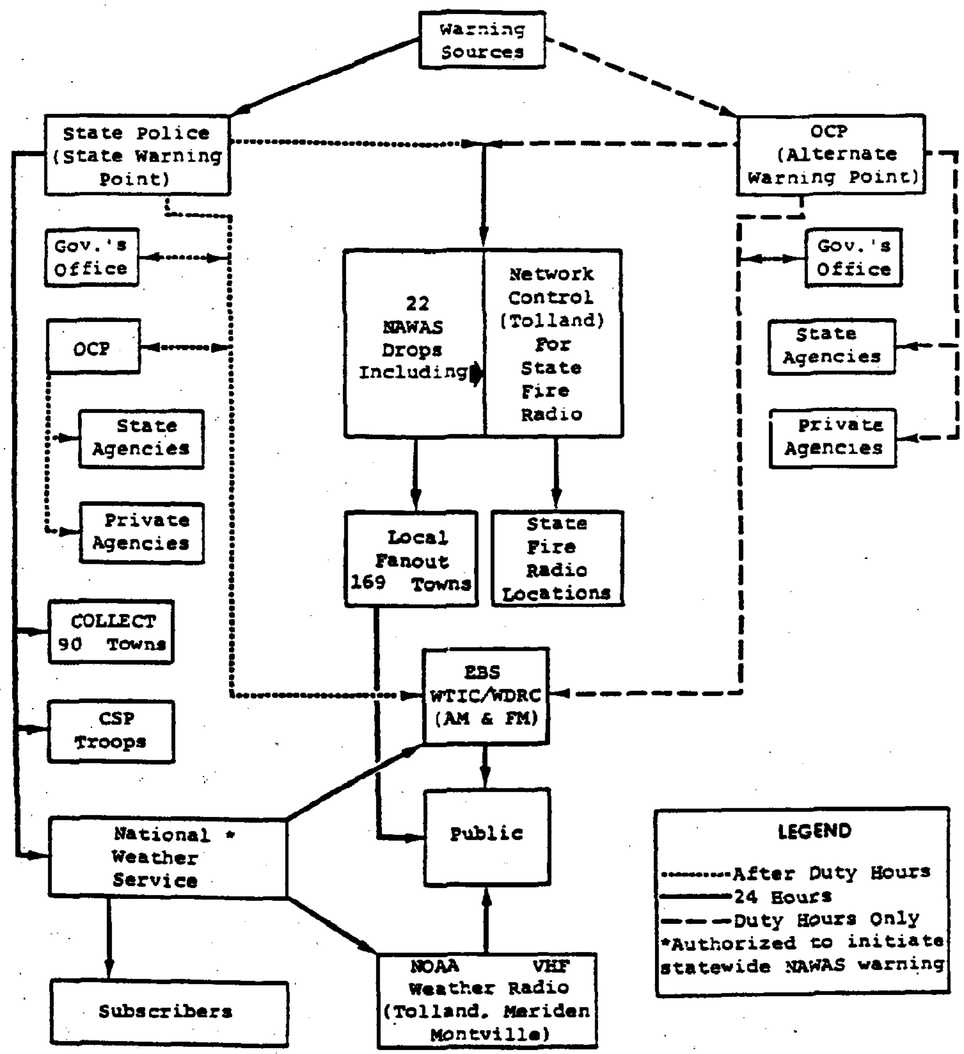
3.2.3 Municipal Procedures

Local cities and towns receive weather warnings through the State warning system, directly from NOAA Weather Radio, and from T.V. and radio stations. According to local officials, flood warnings are often received from NOAA Weather Radio and local media before they are received through the State Warning System. This may reflect, in part, that coastal flood conditions develop over a period of time and the regular weather forecasts usually provide some



SOURCE: Office of Civil Preparedness. 1981. Emergency Operations Plan. CT Office of Civil Preparedness, Hartford, CT.

FIGURE 3.3: Connecticut Communities with NAWAS and COLLECT Systems



SOURCE: Office of Civil Preparedness. 1981. Emergency Operations Plan. CT Office of Civil Preparedness, Hartford, CT.

FIGURE 3.4: Connecticut Warning Flow Chart

indication that a weather watch or warning will be forthcoming well before it is actually issued.

Local officials generally do not rely entirely upon official flood warnings. They also make their own observations of storm surge levels, and make decisions based on these observations combined with their knowledge of areas prone to flooding. Local observations and decisions are particularly important for winter storms. During hurricanes, as indicated during Hurricane Gloria, NWS warnings may affect local decisions more than local observations of flood conditions.

Once a flood warning is received at the local level and confirmed by observations, officials utilize several methods of notifying local residents of specific actions, such as evacuation, that should be taken. The most common methods of disseminating information locally are: areawide sirens, areawide public address systems, car mounted loud speakers, and door-to-door notification. Some towns also use local beach associations and telephone calls to notify area residents. In some towns the local civil preparedness office establishes direct contact with a local T.V. or radio station. Many local civil preparedness officials also maintain telephone contact with the Bridgeport WSO to ensure that they are informed of the latest conditions and forecasts. (32,78,79,80,81, 82,84,85,86,87,88,169,170)

4.0: REVIEW OF AVAILABLE TECHNOLOGY AND PROGRAMS

This section examines available techniques and programs which may be applied to develop a Connecticut coastal flood monitoring network and warning system.

4.1 STORM SURGE AND WAVE MODELS

Theoretical models can be used to predict storm surge levels associated with storms. All theoretical models involve some assumptions and approximation of the actual physics involved in storm surge generation. The simplest models are statistical, and correlate observed storm surge with other meteorological or oceanographic phenomena. With the widespread availability of powerful computers in the 1960's, more complex numerical models were formulated to predict storm surge. A summary of applicable statistical and numerical storm surge models is provided below, and a fuller discussion is presented in Appendix B.

4.1.1 Storm Surge Models

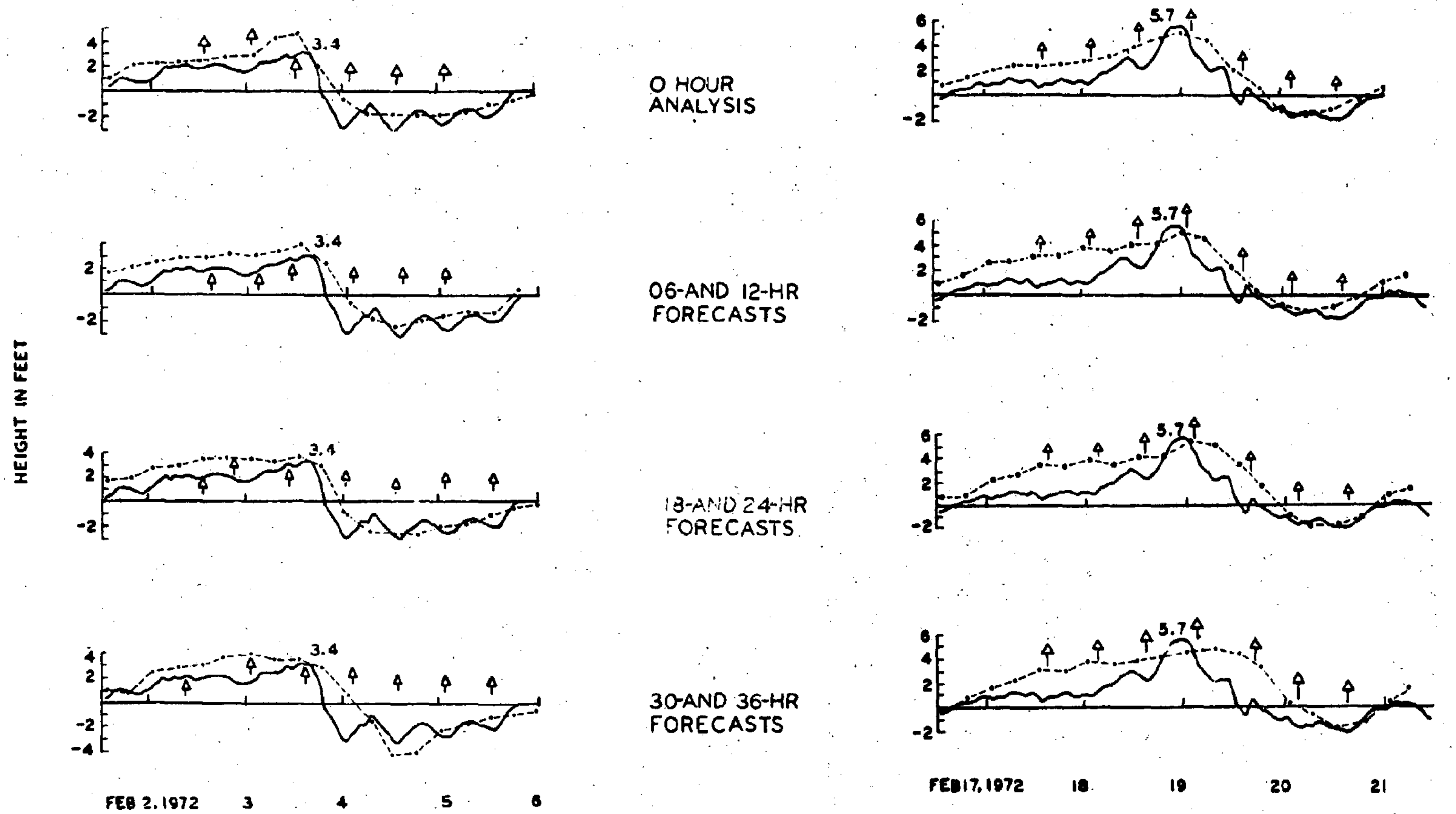
STATISTICAL STORM SURGE STUDIES FOR LIS There have been three major statistical studies of storm surges along the coast of Connecticut. The first, in 1973, was published by the New England Division of the COE (89). The COE revised this work in 1980 (6) during a second study using tide-gage data from stations at Willets Point, NY, and Stamford, Bridgeport, New London, and Stonington, Connecticut. A major decision in the 1980 study was to eliminate the 1938 hurricane data from the statistical model, thereby lowering the 100-year flood estimates, particularly in eastern Connecticut (Figure B.1). (46)

The most recent study was performed in 1982 by Dewberry and Davis, Inc, under contract to FEMA (46), and was essentially a review of the 1980 COE study. The major difference was inclusion of the 1938 hurricane data in their statistical model fit, particularly in eastern Connecticut where the 1938 surge was highest. FEMA adopted the 1980 COE surge profiles, except in the New London area where they were increased to fit the 1938 hurricane data. The resulting profiles (Figure B.2) were used by FEMA in updates to coastal flood insurance studies.

NWS STORM SURGE MODEL FOR EXTRATROPICAL STORMS In the early 1970's, at the request of the NWS Eastern Region Headquarters at Garden City, Long Island, the NWS Techniques Development Laboratory (TDL) developed an empirical model for predicting storm surge during extratropical storms at 12 locations along the U.S. east coast. Separate regression equations were derived for each station by relating observed storm surge at each station to sea level pressure at six-hour intervals at selected points along the east coast and over the Atlantic Ocean. Two versions of the model are available: an automated model that uses sea level pressure data at several locations directly from a NMC computerized database, and a manual one that can be used at WSFOs based on observed sea level pressure. (15,32,71,73,90,69)

Stamford, Connecticut is one of the 12 locations for which regression equations were developed. Review of observed vs. forecast surges, as provided by the NWS (Figure 4.1), indicates that the model consistently over-estimates storm surge at Stamford. The COE, which uses NWS storm surge forecasts as an aid in operating the Stamford Hurricane Barrier, reported that predicted surges are usually higher than recorded surges. No systematic records of predicted vs. recorded storm surge at Stamford have been maintained to measure the forecast accuracy over a long term period. The models have not been recently updated. (39,71,73,75)

NUMERICAL STORM SURGE MODELS To predict the storm surge associated with a particular storm, statistical storm surge summaries are inadequate, and a realistic model of the effects of winds and barometric pressure on the surface of the water of a particular basin is needed. These more realistic numerical models are complex and require powerful computers. They generally use as input some representation of the storm, including central pressure index, wind distribution and speed, storm track and forward speed, and a representation



Forecasts of storm surge based on sea-level pressure forecasts are shown by dots. Solid curves indicate observed storm surges. Arrows indicate times of astronomical high tide. The date of each day is placed at the 1200 EST position. Maximum value of observed surge is placed near peak of each curve.

SOURCE: Pore, N.A., W.S. Richardson, and H.F. Perrotti. 1974. Forecasting Extra-tropical Storm Surges for the Northeast Coast of the United States. NOAA Technical Memorandum NWS TDL-50, Washington, D.C.

FIGURE 4.1: Comparison of Forecast Vs. Observed Storm Surge at Stamford, Connecticut

of the basin, including topography and bathmetry.

<u>NUMERICAL TIDE AND STORM SURGE MODELS USED IN LIS</u> Many numerical tide and storm surge models have been developed for application in different areas and to achieve specific purposes. A few of these models, or portions of larger models, have been used in Long Island Sound. However, only the NWS SLOSH model is presently operational in a Long Island Sound version. The SLOSH model and one additional set of numerical models potentially applicable to LIS are briefly reviewed below, and in more detail in Appendix B.

<u>NWS SLOSH Model</u> -- SLOSH (Sea, Lake, and Overland Surges from Hurricanes) is a numerical model developed for real-time forecasting of hurricane storm surge along the continental shelves, including large estuaries and bays. It was adapted from an earlier model used by NWS, SPLASH (Special Program to List Amplitudes of Surges from Hurricanes), which did not apply to large embayments like Long Island Sound. The SLOSH model includes a storm wind model, which is fed by several time-dependent meteorological storm variables:

(1) Latitude and longitude of storm positions, at 6-hour intervals, for a 72-hour storm track. This begins 48 hours before the storm's nearest approach, and ends 24 hours after the nearest approach.

(2) Storm central pressure at 6-hour intervals.

(3) Storm size (center to region of maximum winds) at 6-hour intervals.

Winds are computed independently by the model, and are not input parameters. Only initial still-water elevations at the boundary regions of the model are required; actual storm surge levels are not input parameters after the model begins running.

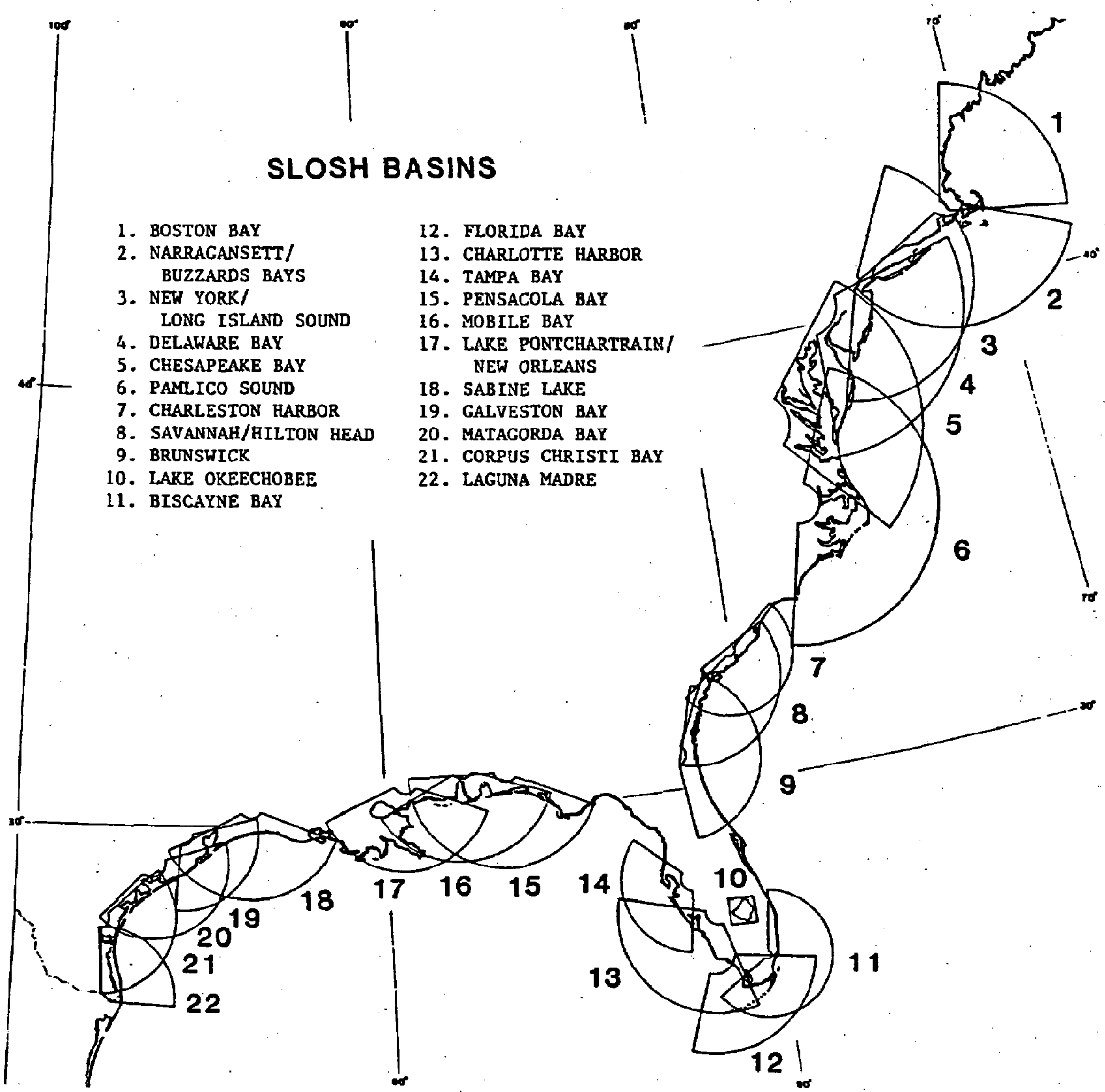
The SLOSH model does not include a tide model within it, because of the uncertainty in timing of tropical cyclones with respect to the surface tide, and because the SLOSH model is also used in a forecast, or "atlas" mode, where the storm surge is simply added to the corresponding tide (see Section 4.4.1). (91,92,93,94)

The SLOSH model is being applied to 22 basins, covering most of the Gulf of Mexico and Atlantic coastal areas, as shown in Figure 4.2. The NWS can run the SLOSH model for a basin as the hurricane approaches within six hours of landfall. As a hurricane or tropical storm moves up the Atlantic coast, the SLOSH model can be run for successive basins. The computers and data input for running the SLOSH model are located at NWS offices in Silver Springs, but output from the model is routed to the NWS National Hurricane Center (NHC) at Coral Gables, Florida.

NWS estimates that the SLOSH model will predict storm surge levels with an error of about +/-20% (e.g., an acceptable predicted range of 8-12 feet for an actual surge of 10 feet at a specific location). Of course, achieving the 20% accuracy level requires that the input parameters be accurate: the basin must be properly described, initial still-water levels at the boundaries must be accurate, and the storm itself must perform in accordance with forecasts (pressure, track, forward speed, etc.). The 20% accuracy level has been verified for many coastal locations (including large embayments such as Galveston Bay and Chesapeake Bay), using observed data from historical storms. For real-time applications of SLOSH, achieving a 20% accuracy level is more difficult, because the storm surge estimates are related to storm track and forward speed, which often vary from forecasts.

Two of the SLOSH basins -- Narragansett/Buzzards Bays (# 2), and New York/Long Island Sound (# 3) -- cover LIS and coastal Connecticut. The New York/Long Island Sound SLOSH basin became operational only within the past year following input of required bathymetry and topographic data at grid coordinates. The model was first used operationally for the Long Island Sound area in September, 1985 for Hurricane Gloria. Because the storm took a more easterly track than forecast, the predicted storm surge in LIS from Hurricane Gloria was significantly greater than the surge that actually occurred.

Although the SLOSH model is now operational for LIS and was used in a real-time mode during Hurricane Gloria, it has not yet been verified using historical storms that crossed over or near LIS. The shallow water in LIS, effect of Long Island on dissipating storms, and other factors peculiar to LIS may adversely affect the accuracy of SLOSH storm surge predictions in LIS. (72,93,95,96,97,98)



SOURCE: Jelesnianski, C.P., J. Chen, W.A. Shaffer, and A.J. Gilad. Undated. SLOSH - A Hurricane Storm Surge Forecast Model. Techniques Development Laboratory, National Weather Service, NOAA, Silver Spring, MD.

FIGURE 4.2: SLOSH Basins Along the Gulf of Mexico and Atlantic Coastlines

Spaulding Models — The Spaulding Models are 2-dimensional, vertically integrated finite difference models. Although primarily tidal models, they could be adapted easily to include storm surge effects. The models appeared to work well on tidal time scales important for coastal flooding.

Since storm surge effects have not been included in the models as applied to LIS, there was no wind stress term, and the time history of development of a wind field could not be included. In a later application of the model for the North Sea, wind stress (or surface stress) was included in the formulation using boundary fitted coordinates. Any future application of the Spaulding-type models must include a storm model for generating vector wind fields. Costs of converting these models to include storm surge effects, including verification, are estimated at between $50,000 and $100,000. If developed, this model could be applied to extratropical storms. Preparation of a series of innundation maps based on multiple storm scenarios (similar to procedures used with the SLOSH model), would probably cost well in excess of $100,000. (99,100,101,174)

4.1.2 Wave Forecasting/Hindcasting Models

Wave forecasting and hindcasting is accomplished by approximating the physics of wave generation and wave transformation using models. In general, wave models can be considered discrete or parametric, although hybrid models have recently emerged. The discrete models are complex, and attempt to directly simulate the wave energy balance or transport equation. In contrast, with parametric wave models the major features of a wave are derived more simply, and require less computation (often relying upon nomographs). There is considerable debate over which type of model is most appropriate for shallow water conditions, such as exist in LIS.

COE WAVE HINDCAST MODEL The COE has historically used a parametric model, as described in the Shore Protection Manual (104), for wave hindcasting. This method is commonly used for generating data on wave characteristics for use in designing coastal protective structures, when empirical wave data is unavailable. More recently, the COE has developed a discrete wave model for use in shallow water.

FEMA WAVE HEIGHT ESTIMATES The National Academy of Sciences developed a methodology for use by FEMA in estimating wave crest elevations associated with any frequency storm. This model is used in the preparation of Flood Insurance Studies and FIRMs. The method includes means for taking account of varying fetch lengths, barriers to wave transmission, and the regeneration of waves likely to occur over flooded land areas. It assumes a high correlation between wave heights and still-water level for a given frequency still-water level. (171, 172,173)

NWS WAVE FORECAST MODELThe National Weather Service uses a wind-wave forecast for generalized offshore wave conditions. This wave forecast is of the parametric type, based largely on empirical relationships between the size of waves generated by specific winds. Three parameters required to use these nomographs are wind speed, fetch length, and wind duration. There is no procedure for collecting actual wave height information for comparison with wave forecasts. (20,32,69)

For the NWS purposes of providing marine forecasts for mariners, generalized wave forecasts may be adequate. However, since these nomograph techniques ignore all details of wave scattering and dissipation, they are not ideal for providing coastal flood warnings to coastal residents.

NUMERICAL WAVE FORECAST MODELS For best results, a numerical wave forecast model is required, which includes the full effects of dissipation and scattering. Several shallow-water, wind-wave models appropriate for providing LIS wave forecasts are available. Costs of adapting one of these models to LIS are estimated to be on the order of $30,000. (174)

4.2 INSTRUMENTATION

Instruments for automatically measuring and recording water levels in the ocean environment have been in use for over 100 years, and for measuring wave characteristics for more than 20 years. A major improvement in recent years has been the replacement of mechanical devices that must actually be in contact with the water surface with "remote" instruments that need not be in contact with the water surface. Typically, these "remote" instruments are mounted on the bottom of the ocean. (27)

Another major advance is the use of microprocessors and other microelectronics to provide rapid sampling and processing of data at remote locations. These data may be stored (typically on magnetic tape cassettes) at the remote site for periodic retrieval, or transmitted to another location by telephone lines, UHF or VHF radio, or satellite. Although initial capital and installation costs of this new generation of instruments is usually higher than the older technology, it has generally proved more accurate and reliable, requires less maintenance, and can be deployed in locations unsuitable for most of the older generation of instruments.

Reliability and maintenance requirements are particularly important for instruments used to obtain oceanographic data. Instruments placed in the ocean must be much more durable than those used in rivers and lakes in order to withstand corrosion, biological fouling, abrasion from sand scouring, and damage from wave forces. The following sections provide an introduction to the principal types of instruments available for obtaining tide, storm surge, and wave measurements.

4.2.1 Tide and Storm Surge Measurements

PRESSURE SENSORS Pressure sensors measure water level indirectly. The actual measurement is of hydraulic pressure. Some sensors also measure atmospheric pressure, and this portion of the total pressure must be removed in order to obtain an accurate measurement of water level (corrective procedures are often incorporated within the sensor). Pressure gages do not require a stilling well. Still-water level is normally determined by rapidly taking many samples over a fixed time period and averaging the results. Three types of pressure gages are available to measure tide and storm surge levels: bubbler gages, strain gage pressure sensors and quartz pressure sensors.

Bubbler gage: Bubbler gages, of the type now in use in LIS by NOS and USGS, use compressed air released through a bubble orifice at the end of a length of tubing on the ocean floor. The changing head (water level) above the bubble orifice causes a corresponding pressure change, which is reflected in a manometer, which is usually connected to an electro-mechanical chart recorder or some type of transmitter. Bubbler gages do not require a stilling well, and the bubble orifice can be placed several hundred feet from the compressed air source and recording/transmitting equipment. A typical bubbler gage installation is shown in Figure 2.10. (107,108)

Strain gage pressure sensor: Strain gage pressure sensors utilize some type of variable resistance sensor (e.g. hydraulic, semiconductor, or conductivity) in combination with an electrical circuit. As pressure from the water (and atmosphere) column changes, resistance changes (voltage varies). Voltage change is the actual measurement. Sensitivity of strain gage pressure sensors may vary considerably depending upon the specific type and quality of gage, but a typical gage may have a resolution of .1% and an accuracy of .5% of the total measurement range (e.g. for a measurement range of 30 feet, a resolution of about 1/2 inch and an accuracy of about 2 inches). Strain gage pressure sensors are usually highly temperature sensitive, and readings must be temperature corrected (thermistor often included in gage to permit automatic correction). Strain gage pressure sensors may vary in cost from as low as $200 to about $2,000.

Quartz pressure sensor: Quartz pressure sensors utilize a quartz crystal with a frequency of oscillation that is a function of pressure. The frequency of oscillation is the measurement method. Quartz pressure sensors are much less temperature sensitive and have lower power requirements than strain gage pressure sensors. They are also more sensitive and a typical resolution is .005% with an accuracy of .01% of the total measurement range. Quartz pressure sensors cost in the range of $2,000 or slightly more.

Tide gages using either strain gage or quartz pressure sensors incorporate electronics packages that control the sampling rate, length of sample (integration time), and averaging of samples to filter out the effects of waves. For example, to obtain one water level sample, the instrument might average all instantaneous water level readings over a 60-second period in order to filter out wave action. Most instruments have variable sampling rates.

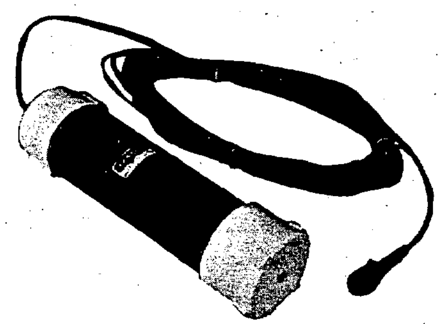
Strain gage and quartz pressure sensors are housed in a water-tight casing (such as plastic or aluminum), and mounted near the ocean floor. Some units are completely self-contained, and store data on magnetic tape within the gage. Tapes must be periodically retrieved and replaced. Other gages are connected by underwater cable to data recording and/or transmitting units located in nearby instrument houses.(109,110) Some typical pressure gages are shown in Figure 4.3.

ACOUSTIC SENSOR: Acoustic sensors measure the time it takes for acoustic pulses or "shock waves" to move between the water surface and calibrated reference points. The system described here is one developed by Bartex, Inc. A pulse frequency generator/transmitter/ transponder unit sends acoustic pulses through a small sounding tube which is mounted on a pier or other structure and extends from above the water level into the water to the lowest level to be measured (35 feet maximum range). A reference source is contained within the sounding tube. As the pulse travels down the tube, it is reflected first by the reference source and then by the water surface. The transducer converts the reflected acoustic pulses (echos) to electrical pulses. An electronics package measures the return time for each pulse reflected by the water surface compared to that from the reference source, and the water level is determined. This system has a resolution of .01 foot and an accuracy of about .09 foot over the 35 foot maximum range. Measurements may be automatically initiated at intervals of one to 99 minutes, or the unit may be interrograted at any time. Output data is compatible with various telemetry methods. The Bartex gage has been selected by NOS for initial use and testing in its next generation of water level stations (see Section 4.3.1). The Bartex gage, including digital interface, costs approximately $2,600. (109,111,112,113,114) The Bartex acoustic gage is shown in Figure 4.4.

OTHER TYPES OF GAGES: Several other types of water level measurement gages have been developed, including: float and counterweight (see Section 2.4.2); resistance wave staff; microwave radar; capacitance type probes; and optical devices that read a staff gage floating within a stilling well. (109,110)

For various reasons, none of these gages are as well suited to measuring tide and storm surge levels as the pressure and acoustic gages described above.

Sierra-Misco Model 5050LL-PT
Liquid Level Sensor
(Sierra-Misco, Inc., Berkeley, CA)



Sea Data Model 635-6 Tide Recorder
(Sea Data Corporation, Newton, MA)

InterOcean Model STG 7500 Tide Gauge
(shown outside of casing)
(InterOcean Systems, Inc., San Diego, CA)

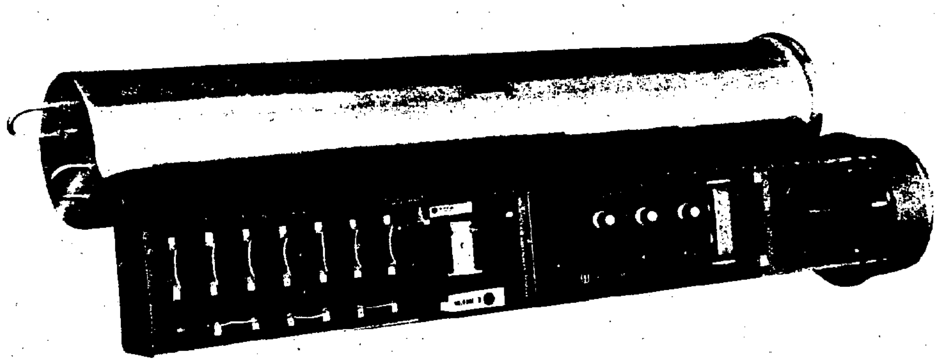


FIGURE 4.3: Typical Pressure Transducer Type Tide Recorders

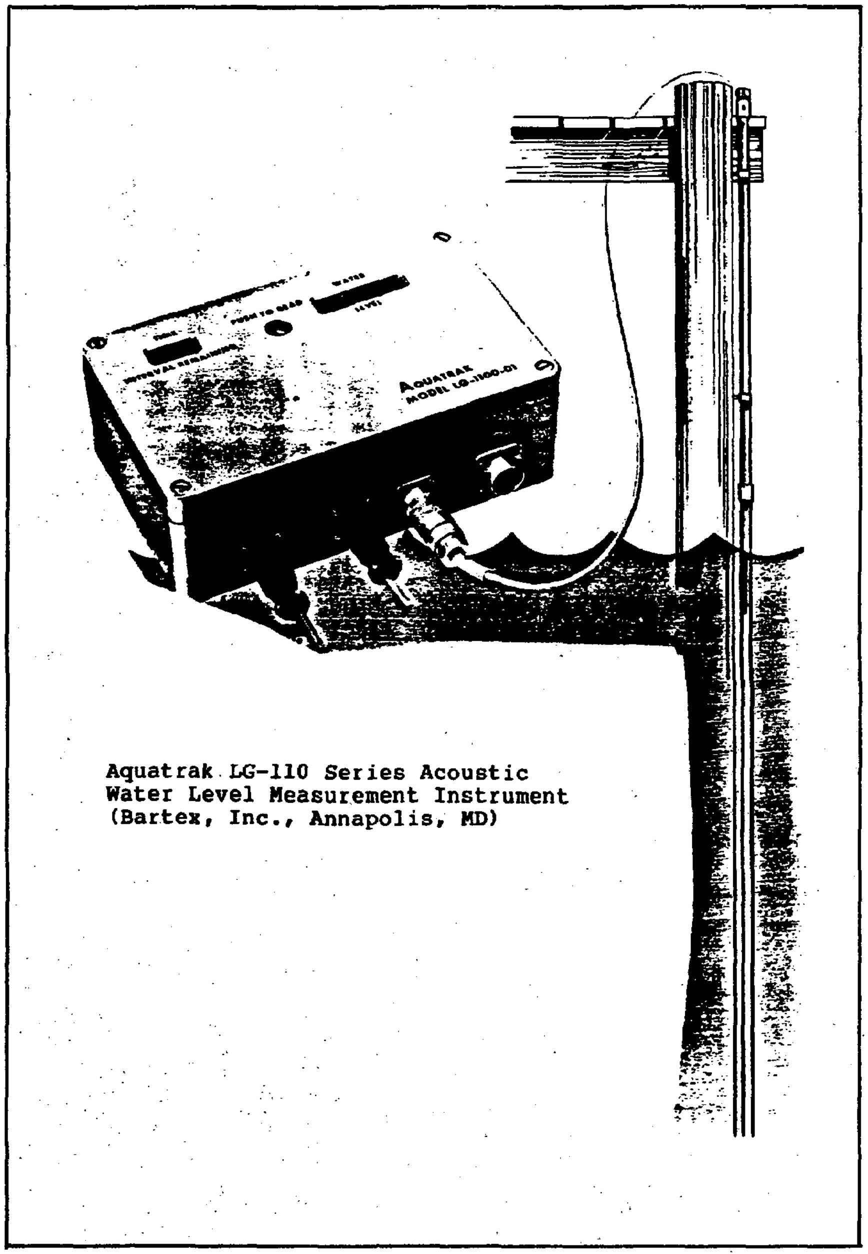


FIGURE 4.4: Acoustic Type Tide Gage

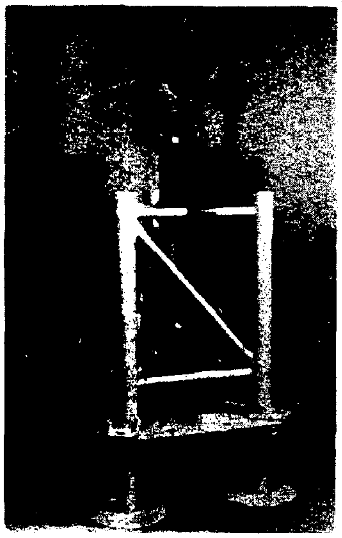
4.2.2 Wave Measurements

There are many ways to measure waves in the ocean, and a vast literature on measurement techniques exists. Central requirements are reduced maintenance, little drift in instrument calibration, ease of maintenance or replacement, accuracy, reliability, and ease of adaption to this long-term gaging task. Different instrumentation may be chosen depending upon whether waves are to be measured in deep water offshore, or shallow water nearshore, and whether measurements are to include wave directional as well as energy characteristics.

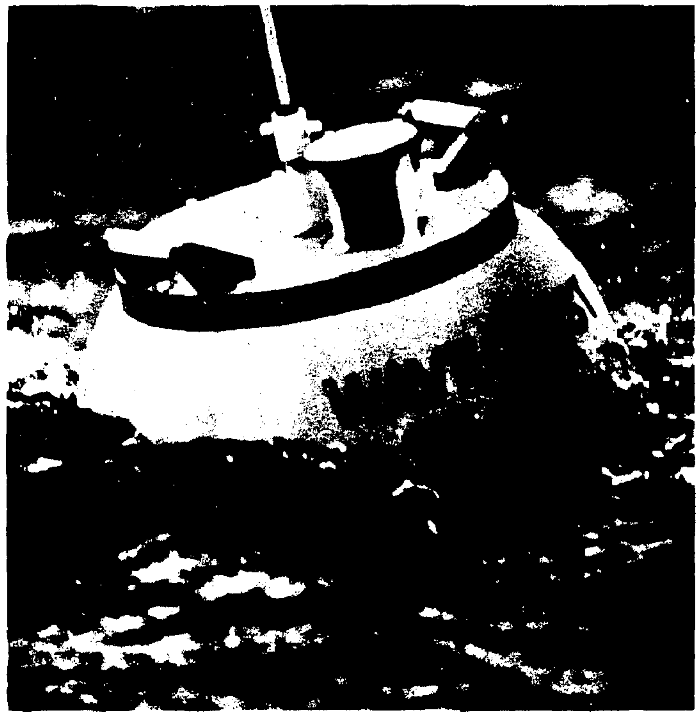
WAVE BUOYS: Wave buoys are commonly used to measure waves (and tides) in deep water offshore locations. Typical modern wave buoys are floating spheres that follow the movement of the water surface. Contained inside the sphere is an accelerometer which measures the vertical acceleration of the buoy, yielding data on wave height and wave frequency. Buoys are normally moored to the ocean bottom. Buoys may record data on magentic tape for periodic retrieval, or may transmit data by radio frequency or satellite. (110) Figure 4.5 illustrates typical wave buoys.

PRESSURE GAGES: Bottom-mounted strain gage and quartz pressure sensors may be used to measure wave characteristics as well as tide and storm surge levels (see Figure 4.5). For measuring wave characteristics, sampling is generally based upon "burst," rather than continuous sampling. Determination of sampling frequency depends upon several factors, including depth of water, and commonly ranges from 1-2 Hz (1-0.5 cycle/second). To obtain spectral wave characteristics, a fourier transformation is performed on time series data, commonly based on sample sizes in multiples of two. Standard sample sizes, or bursts, are 1,024, 2,048, etc. A 1,024 point sample at 1 Hz results in approximately 17 minutes of data. Analysis of data yields values for significant wave height, significant wave period, total wave energy, and the fraction of total energy within each period, as illustrated in Figure 4.6.

Wave gages may be self-contained, with all necessary data processing electronics and data storage capability built into the gage. Other options include internal data processing, with transmission to a near shore station by underwater cable; or data collection only, with all data processing occurring at a shore station



Sea Data Model 635-9
Directional Wave Recorder
(bottom mounted, shown
in mooring tripod)
(Sea Data Corporation,
Newton, MA)



NBA Model WBU-1 Wavecrest Wave Profiling Buoy
(NBA (Controls) LTD., Farnborough, England)

FIGURE 4.5: Typical Wave Measurement Gages

IMPERIAL BEACH ARRAY.ENERGY
DEC 1985

PERCENT ENERGY IN BAND
(TOTAL ENERGY INCLUDES RANGE 2048-4 SECS)
BAND PERIOD LIMITS (SECS)

PST DAY/TIME		SIG. HT (CM.)	TOT. EN (CM.SQ)	22+	22-18	18-16	16-14	14-12	12-10	10-8	8-6	6-4
26	0801	86.7	469.6	4.1	0.7	3.7	42.9	20.8	9.6	12.3	5.0	1.3
26	1401	80.2	401.9	3.1	0.7	1.8	34.2	30.2	16.0	7.5	5.4	1.6
26	2001	77.3	373.8	3.4	0.3	4.0	38.1	34.5	7.6	6.4	5.1	1.1
27	0201	80.5	405.5	2.0	0.3	1.7	26.4	33.6	25.8	6.2	3.5	0.9
27	0801	71.2	316.6	2.8	0.6	1.8	26.5	37.5	17.0	7.9	4.6	1.8
27	1401	59.8	223.5	4.7	1.1	3.2	25.3	38.8	11.8	8.9	4.6	2.0
27	2001	66.5	276.1	3.8	1.0	3.4	19.4	40.7	20.5	6.4	4.3	1.1
28	0201	64.1	257.0	2.4	3.6	6.7	27.1	36.6	14.1	4.6	3.1	2.2
28	0801	71.9	323.1	3.3	3.6	11.2	42.6	20.2	10.9	4.1	2.9	1.7
28	1401	76.2	362.5	3.5	2.2	12.5	21.2	39.5	14.4	2.2	3.2	1.6
28	2001	85.0	451.9	2.3	4.3	7.8	22.7	40.3	15.8	2.6	2.9	1.8
29	0201	76.6	367.1	4.2	1.5	9.0	33.7	30.3	13.9	3.7	2.9	1.2
29	0801	72.6	329.0	5.6	1.0	5.9	26.5	41.2	13.1	3.4	2.5	1.4
29	1401	72.3	326.6	5.5	1.0	7.1	14.5	46.0	19.6	3.7	1.9	1.1
29	2001	68.4	292.1	4.1	1.1	16.9	14.1	38.7	16.5	6.0	2.4	0.8
30	0201	63.7	253.5	6.1	7.2	14.8	8.7	33.6	19.9	6.2	2.8	1.0
30	0801	78.7	387.5	6.0	13.6	4.7	11.5	26.2	24.5	9.7	2.8	1.3
30	1401	80.1	400.7	5.0	13.7	14.2	6.6	14.0	29.4	11.3	3.2	3.0
30	2029	91.7	525.9	3.6	7.5	33.7	10.1	8.5	12.9	12.3	7.7	4.2
31	0201	99.6	620.6	2.9	5.5	33.7	10.5	14.1	12.2	8.0	7.6	5.9
31	0801	113.0	797.6	4.4	5.0	28.6	14.6	19.0	9.3	10.1	6.2	3.1
31	1401	93.8	549.8	5.1	3.7	23.0	19.8	13.7	9.6	9.5	9.7	6.5

IMPERIAL BEACH ARRAY.ENERGY
DEC 1985

PERSISTENCE
CONSECUTIVE DAYS (1 OR MORE) SIGNIFICANT
WAVE HEIGHT IS -N- METERS OR LESS

METERS	DAYS			
0.5	1.			
1.0	1.	1.	7.	5.
1.5	1.	3.	10.	7.
2.0	2.	28.		
2.5	31.			
3.0	31.			
3.5	31.			
4.0	31.			
4.5	31.			
5.0	31.			
5.5	31.			
6.0	31.			

MAXIMUM DAILY SIGNIFICANT WAVE HEIGHT FOR DEC 1985

DATE (DEC)	1	2	3	4	5	6	7
SIG.HT (M.)	1.6	0.8	2.4	1.6	1.6	1.7	1.5

DATE (DEC)	8	9	10	11	12	13	14
SIG.HT (M.)	1.8	1.7	1.4	0.9	1.2	1.5	1.2

DATE (DEC)	15	16	17	18	19	20	21
SIG.HT (M.)	0.9	0.5	0.6	0.8	0.5	0.4	0.7

DATE (DEC)	22	23	24	25	26	27	28
SIG.HT (M.)	1.0	1.1	1.6	1.0	0.9	0.8	0.9

DATE (DEC)	29	30	31
SIG.HT (M.)	0.8	0.9	1.1

SOURCE: U.S. Army Corps of Engineers, and California Department of Boating and Waterways. 1986. Coastal Data Information Program, Monthly Report, December 1985. Monthly Summary Report No. 119.

FIGURE 4.6: Sample Analysis of Wave Parameters

(data transmission by underwater cable). (110)

Several pressure gages may be arranged in an array to obtain directional wave data. Directional wave recorders are also available that measure wave direction by means of an electromagnetic flow sensor. (110,115)

4.2.3 Meteorological Instruments

An enormous variety of meteorological instruments is available for automatically sampling a wide range of meteorological conditions. Meteorological parameters most applicable to a coastal flood monitoring network and warning system are wind speed and direction and barometric pressure. No review of the different types of instruments available is provided in this report.

4.2.4 Data Transmission and Processing

Microprocessor technology has greatly increased the speed of data processing and has made real-time data collection, transmission, and processing practicable. With the availability of microcomputers in the early 1980's, this real-time capability is now available to small scale users at a reasonable cost. In the simplist terms, this technology involves transformation of raw data into a digital format for processing and transmission; transmission by telephone lines, radio frequency, or satellite; and transformation of processed data into appropriate statistical data, engineering terms, graphics, or other appropriate forms. Unfortunately, there is a great lack of standarization in the technology by which data are collected, transmitted and processed. Consequently, specific applications such as a Connecticut flood monitoring network generally cannot be deployed simply by assembling individual components from different vendors. Almost inevitably, some off-the-shelf components will not be fully compatible with others, requiring that some hardware and/or software components be customized.

As an example, the Connecticut ASERT system is not compatible with some other real-time meteorological, hydrologic and oceanographic systems, particularly some wave measurement systems. One limitation is that ASERT is a one-way communications system; it transmits data only from the remote field stations to a base station. The field units may not be queried (interrogated) from the base station (with ASERT the user may interrogate the base station unit for data stored in the computer memory). By contrast, some storm surge and wave measurement systems are based on two-way communications. A user at the base station may directly interrogate the field station to obtain the most recent measurements. If the sensor and related electronics package permit, the user may also reprogram the sensor to change sampling rate or perform other modifications. Two-way communications systems are more expensive than a one-way communications system. A two-way system would not be compatible with the radio repeater stations used with ASERT.

ASERT is also an event reporting system: field stations transmit rainfall and streamflow data at random times whenever a sample differs from the previous sample by a predetermined amount (meteorological measurements are transmitted on a timed basis). Because transmission time of a single piece of data is brief less than .25 second) very few individual transmissions will be lost due to interference. Lost data units (such as may occur during an intense rain storm) are not critical to overall data quality since all data is transmitted in equal units (e.g. 1.0 mm of rainfall), and the data coding and software permit all data transmissions to be accumulated even if individual units are lost. Wave data are normally transmitted on a timed basis to avoid interference and loss of data. Unlike rainfall, streamflow, and storm surge, every piece of wave data is required in order to obtain wave spectral parameters. Consequently, measurements of full wave characteristics cannot be sent over the same radio frequencies or use the existing radio repeaters and base station receivers that are part of ASERT without compromising the wave data. (61,110,116, 117,174)

4.3 COASTAL MONITORING, FORECAST AND WARNING PROGRAMS

Several significant developments are underway or planned which may influence the way in which a Connecticut coastal flood monitoring network and warning system should be designed and operated. In addition, several existing real-time monitoring and warning networks provide useful information for design considerations.

4.3.1 Federal Program Activities

FEMA HURRICANE PREPAREDNESS PROGRAM FEMA, in cooperation with NWS, the COE and coastal states, has underway a Hurricane Preparedness Program. Among the objectives of this program is the development of special evacuation elements for inclusion in state and local emergency operations plans, in response to the approach of hurricanes in high-risk, high-population areas. A complete Hurricane Preparedness Study for a region may require 3-5 years to complete and cost on the order of $2,000,000. The studies are federally funded with contributions from FEMA, NWS, and COE. State and local officials contribute staff time to work with federal agencies.

One of the first elements of a Hurricane Preparedness Study is performance of a Hurricane Hazard Analysis. This is an analysis of the expected hazards that would require the temporary emergency relocation of some portion of the population. The results of the analysis form the basis for determining vulnerable areas that require evacuation. The principal tool used in the hazard analysis is the NWS SLOSH model. Instead of running SLOSH in a real-time mode, it is used to run a series of simulations of possible hurricanes. Normally, the five storm intensities of the Saffir/Simpson scale are simulated. Three hundred or more simulation runs may be performed, representing various combinations of hurricane intensity, track, size, and forward speed.

Each hypothetical hurricane simulated by SLOSH would confront an area with one of many distinct hazard scenarios which, in turn, ultimately make up the evacuation scenarios, or levels. The output of the SLOSH model provides four major types of information on the effects of the simulated hurricanes. They are: 1) Surface envelope of highest surges above mean sea level; 2) Time histories of surges at selected gages or grid points; 3) Computed wind speeds at selected gages or grid points; and 4) Computed wind directions at selected gages or grid points. The results of individual surge model simulations (and/or groups of common intensity/track types, termed Maximum Envelopes of Water - MEOWs) will provide predicted storm surge elevations. Innundation maps based on these predicted storm surge elevations will indicate vulnerable coastal areas and will form the basis for several distinct evacuation levels.

According to FEMA and NWS personnel, current plans are to begin the Hurricane Hazard Analysis, including running hurricane simulations for the Narragansett/-Buzzards Bay SLOSH basin (Figure 4.2 and B.3), in the latter part of calendar year 1986. A definite schedule for beginning a Hurricane Hazard Analysis for the New York/Long Island Sound SLOSH basin (Figure 4.2 and B.4) has not yet been established, but it may begin in FY 87. The start date will depend upon available funding and priorities among basins. Once the simulations for these basins have been run and MEOWs developed, the MEOWs will form the basis for evacuation notices; not the forecast storm surge from a real-time SLOSH run. Although NWS will continue to run SLOSH in a real-time mode as a hurricane approaches, it will base all public warnings for evacuation purposes on the MEOWs applicable to the forecast track, intensity and forward speed of the hurricane. The accuracy of the MEOWs relative to the actual storm surge will largely depend upon the accuracy of the hurricane forecast.

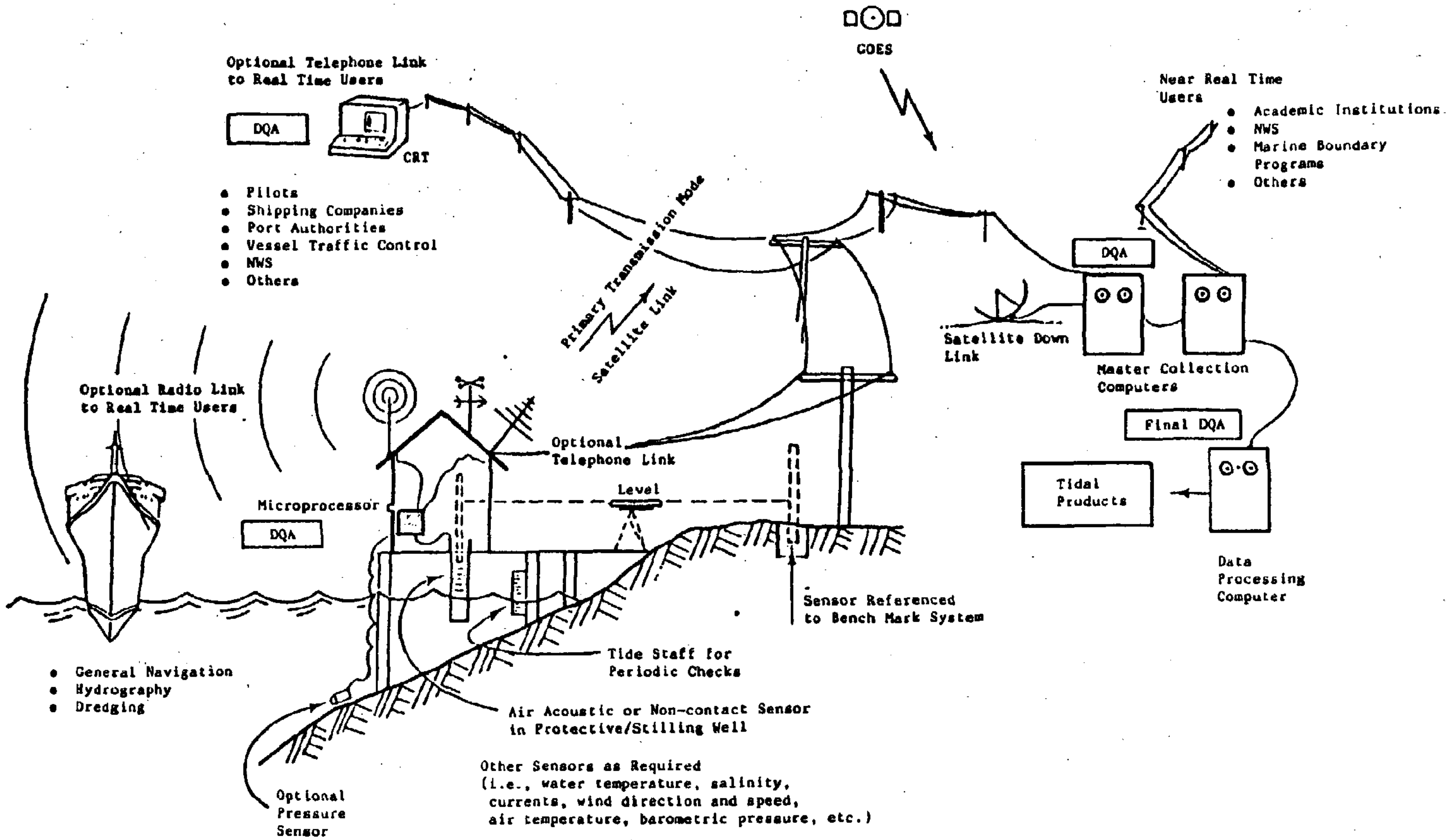
As indicated in Section 4.1 and Appendix B, the SLOSH model may have some limitations as applied to LIS. Connecticut (as well as New York and Rhode Island) officials should work closely with the FEMA, NWS and COE in the application of the model to LIS to ensure the most favorable results. (71,72,93,96,97,118, 119,120, 121,122)

NOS NGWLMS PROGRAM The NOS operates and maintains the National Water Level Observation Network (NWLON) to accomplish its mission requirement for measuring and disseminating tides and water level data. Because the technology used to support the NWLON is aging and obsolete, NOS will replace it with a modernized system, the Next Generation Water Level Measurement System (NGWLMS). NGWLMS is a fully integrated system encompassing new technology sensors and recording equipment, multiple data transmission options, and an integrated data processing, analysis and dissemination system.

NOS has selected an acoustic gage (manufactured by Bartex, Inc., and described in Section 4.2) for measuring tides and storm surge, with a pressure gage as backup. The acoustic gage will receive further evaluation during initial installations, so its selection is not entirely assured for the entire new system. NOS apparently has no plans to measure wave characteristics (most NOS gage stations are located in areas at least partially protected from wave action). Information will be collected and transmitted in near real-time. The primary means of data transmission will be by GOES Satellite. Radio and telephone telemetry is also planned. Figure 4.7 illustrates the proposed system. NOS plans to make available to interested users a software program (floppy disk for use in a microcomputer) which will enable the users to obtain both actual (near real-time) and predicted (as in published tide tables) tide levels by connecting with any NOS gage through a telephone modem.

NOS hopes to have NGWLMS fully operational in the late 1980s or early 1990s. However, the schedule for upgrading tide stations has not been finalized and will depend upon several factors such as need for equipment replacement, geographic spread of initial installations to be used for continued testing and evaluation, and available budget. NOS has indicated that it would invite interested states to enter into cooperative agreements for early installation of gages in their area (in Connecticut one of the two NOS gages could potentially be included as an early installation). (27,98,123, 124,125)

NWS TELEMETRY UPDATE The NWS generally does not own and operate its own tide gage stations. But at many NOS gage stations, such as Bridgeport, the NWS does operate a tide level recording unit off of the NOS primary gage. The existing equipment (Bristol Metameter) is old and no longer reliable, so the NWS is now installing new telemetry instrumentation (Handar, Inc., Model 540A) at selected NOS gage stations. This new instrumentation is intended to provide near real-time data to the NMC in Silver Springs to improve NWS forecasting ability, as well as continue to have real-time data available in local NWS offices. Use of this new equipment is intended to be temporary: as NOS upgrades its NWLON system with the new gages and telemetry, NWS will remove its Handar instruments and redeploy them in riverine areas. A Handar unit is expected to be installed by NWS at the Bridgeport NOS gage in the very near future (unit already available at Bridgeport WSO office). One disadvantage to the Handar equipment is that it will not provide a continuous display and chart record of tide levels as the present Bristol equipment does. Instead, local NWS personnel must interrograte the gage to obtain tide levels. (32,33,34,98,117, 123,124,125,126,127)



SOURCE: Deibel, Lawrence E., and Barbara A. Zumwalt. 1985. Next Generation Water Level Measurement System Program. By The Mitre Corporation for National Ocean Service, NOAA, Dept. of Commerce.

FIGURE 4.7: National Ocean Service NGWLMS System

FEDERAL INTERAGENCY STANDARDS COMMITTEE In response to the lack of standarization in the equipment manufactured for measurement, transmission and analysis of meteorologic, hydrologic and oceanographic data, a federal interagency standards committee was formed in the summer of 1985. The first meeting of the committee was scheduled for October, 1985. (98,128)

FEMA IEMIS PROGRAM FEMA has developed an Integrated Emergency Management Information System (IEMIS) that is intended to allow FEMA headquarters, training center and regional offices, and state and local governments to perform data sharing, joint planning, exercising and — potentially — operational coordination. Currently, the system is on-line at the FEMA headquarters, regional offices, and training center. IEMIS uses a standard national map for display of information. The system originated with FEMA's Radiological Emergency Preparedness Program, and future developments are planned to include adaptations for hurricane evacuation and evacuations below failed dams, among others.

Currently, FEMA is cooperating with the NWS and City of Tulsa, Oklahoma in development of an operational flood warning system on IEMIS. FEMA indicated that it is seeking other states, localities and private contractors to participate in pilot projects. Other states actively involved with IEMIS include Louisiana and Massachusetts. Connecticut is not presently pursuing operational involvement with IEMIS. Although IEMIS program goals are ambitious, it is unclear at this time whether there is a real need or opportunity for a Connecticut coastal flood monitoring network and warning system to be operationally compatible with IEMIS. (121,129,130,131,132,133, 134)

4.3.2 Real-Time Programs

COASTAL FLOOD WARNING PROGRAMS

Tsunami Warning The NWS, in cooperation with NOS, operates a tsunami warning system in the Pacific Ocean. Wave data is telemetered to a central receiving station. When an earthquake occurs or wave characteristics indicate the potential for a tsunami, the gages are signaled to increase their sampling rate. (27)

Harrison County, Mississippi Water Level Monitoring System The Harrison County, Mississippi Office of Civil Preparedness (Gulfport area) is currently developing a real-time flood warning system. This system is very similar to the Connecticut ASERT/ALERT system, and will include 3 river and 3 coastal sites. Data will be transmitted by VHF radio to the Civil Preparedness office. Officials feel this system will provide them with accurate information on storm surge without having to send out observers under dangerous conditions. Wave characteristics will not be measured, nor is any prediction of storm surge planned. (163,164)

Thames River Estuary, England An operational system in the Thames River Estuary provides the Canterbury City Council with real-time data on tide and wind conditions. One station (pressure transducer) in the harbor at Whitstable, transmits tide and wind data at regular intervals by dedicated telephone line to the Council offices in Canterbury. A similar station out in the estuary transmits data by radio frequency. The receiving station is equipped with a modem and a speech synthesizer, so that it may be accessed from any location and a synthesized voice will report tide and wind conditions. (165)

Ganges River/Bay of Bengal Flood Warning Network In cooperation with the National Aeronautics and Space Administration (NASA), the government of Bangladesh has installed a network of 10 tide gages along the Ganges River and a fully equipped meteorological buoy in the Bay of Bengal. Data are transmitted through the ARGOS Satellite System to a ground station in Dacca, the capitol of Bangladesh. Early warnings provided by this system were credited with saving numerous lives during the disastrous May 1985 cyclone which struck the Bay of Bengal. (166,167)

NAVIGATION PROJECTS

New York Harbor Tidal Gage System The "New York Harbor Tidal Gauge System" is a cooperative effort between NOS, New York Department of State and the Maritime Administration of the Port of New York (MAPONY). It provides real-time water level data from four NOS tide gages. The system is oriented primarily towards navigation, but can also be used for other purposes, including input to weather forecasts. Tide level data from the four gages are available via telephone telemetry to a microcomputer (IBM PC) at MAPONY offices, the New York WSFO and system subscribers. Data are available on a computer terminal display or paper printout (See Figure 4.8). No provision has been made for permanent data storage.

System installation costs of $250,000 were provided by the New York Department of State. Anyone may subscribe to the system with a $100 connection fee and $100 monthly charge. A compatible microcomputer or terminal and a modem are all that is required to access the system. The system was intended to be financially selfsupporting through subscriber fees, but there are currently only three paid subscribers and the possibility exists that the system may be shut down. Although reportedly providing accurate and useful information, the system has suffered reliability problems because of difficulties with the telephone lines.

The primary users of the information are the NWS and the Sandy Hook Pilots Association (movement of ships in and out of New York Harbor). The New York WSFO uses data from the system as input to its weather and storm surge forecasts, including data during Hurricane Gloria. Although proponents of the system (including NOS and MAPONY) speak of the tremendous financial savings available to ship owners by being able to move ships sooner or more fully loaded, most ship owners apparently remain unconvinced and have been unwilling to provide financial support for the system.

The New York WSFO reported that it found real-time information from the network to be of great value during Hurricane Gloria. One station was not operational during Hurricane Gloria because of problems with the telephone lines, another gage was operational during only part of the storm, and two gages were operational through the entire storm. (22,125,139,140,141,142,143, 144,146,147,148,149,153)

<u>Delaware Bay Navigation Project</u> NOS has funded a special Delaware Bay Program which incorporates a numerical model of tide levels and currents in the Bay. The model, combined with four acoustic tide gages, several current meters, and meteorological instruments provides real-time and predicted data on currents and tide levels in Delaware Bay. This information is telemetered

PORT OF NEW YORK TIDE TELEMETRY SYSTEM MAR 01

REMOTE STATION	SAMPLE TIME [EST]	TIDE LEVEL [FEET]	WIND SPEED [KNOTS]	WIND DIRECT [DEG-T]	WIND GUST [KNOTS]	DATA QUALITY CODE	SYSTEM STATUS ncdpb
SANDY HOOK	09:18	+00.6	09	260			
BATTERY	09:18	+00.5					
BERGEN PNT	09:18	+00.8	05	224			
WILLETS	09:18	+02.7					
SANDY HOOK	09:24	+00.6	09	258			
BATTERY	09:24	+00.5					
BERGEN PNT	09:24	+00.7	05	225			
WILLETS	09:24	+02.6					
SANDY HOOK	09:30	+00.5	09	257			
BATTERY	09:30	+00.5					
BERGEN PNT	09:30	+00.7	05	227			
WILLETS	09:30	+02.5					
SANDY HOOK	09:36	+00.5	09	258			
BATTERY	09:36	+00.5					
BERGEN PNT	09:36	+00.7	07	200			
WILLETS	09:36	+02.4					
ANDY HOOK	09:42	+00.5	09	258			
BATTERY	09:42	+00.5					
BERGEN PNT	09:42	+00.6	08	203			
WILLETS	09:42	+02.3					
SANDY HOOK	09:48	+00.5	04	258			
BATTERY	09:48	+00.5					
BERGEN PNT	09:48	+00.6	06	216			
WILLETS	09:48	+02.2					
SANDY HOOK	09:54	+00.6	04	258			
BATTERY	09:54	+00.4					
BERGEN PNT	09:54	+00.6	08	208			
WILLETS	09:54	+02.1					

SOURCE: Maritime Administration of the Port of New York, New York, New York

FIGURE 4.8: Sample Display of Tidal Data from New York Harbor Tidal Gage System

via VHF radio to several computer terminals, including portable terminals for use on ships by Delaware Bay Harbor Pilots. The numerical model has been kept on-line by NOS at a cost of several thousand dollars per month. Recently, the system was taken off-line because of costs. Although the model predicts water levels up to 12 hours in advance, it was not designed to provide an accurate prediction of storm surge (does not include all necessary wind stress fields). (124,125,150,151)

Additional NOS Supported Navigation Projects NOS has also helped develop, in cooperation with the COE, a real-time navigation system in the Columbia River, Oregon; recently entered into an agreement with the Port of Miami; and is discussing agreements with ports at Charleston, South Carolina and Baltimore and Annapolis, Maryland in Chesapeake Bay. Although NOS indicated that it can no longer provide funding for pilot projects, it will enter into cooperative agreements with states and other jurisdictions to provide technical assistance in the development of real-time navigation systems. (27,124,125,153)

Other Real-Time Navigation Programs Other real-time navigation programs are in operation around the country, including two privately operated systems in San Francisco Bay. One of these (apparently no longer operating) consisted of seven tide stations transmitting every six minutes. It was designed to be self-supporting, charging users a fee of $25 for each ship transit. Another private firm operates a single tide gage at the San Francisco Bay Bridge. Since this gage is tied to an ALERT type system, a typical graphic display from this gage is shown as Figure 4.9. Many tide gages with real-time data transmission are used by dredging operations in the Great Lakes and other locations. (61,154,155,156,157)

National Academy of Sciences Report The NAS, National Research Council, Marine Board has established a Committee on Information for Port and Harbor Operations to examine the potential for real-time navigation in ports and harbors. The committee report is due out approximately April, 1986. No information is currently available from NAS. (143,152)

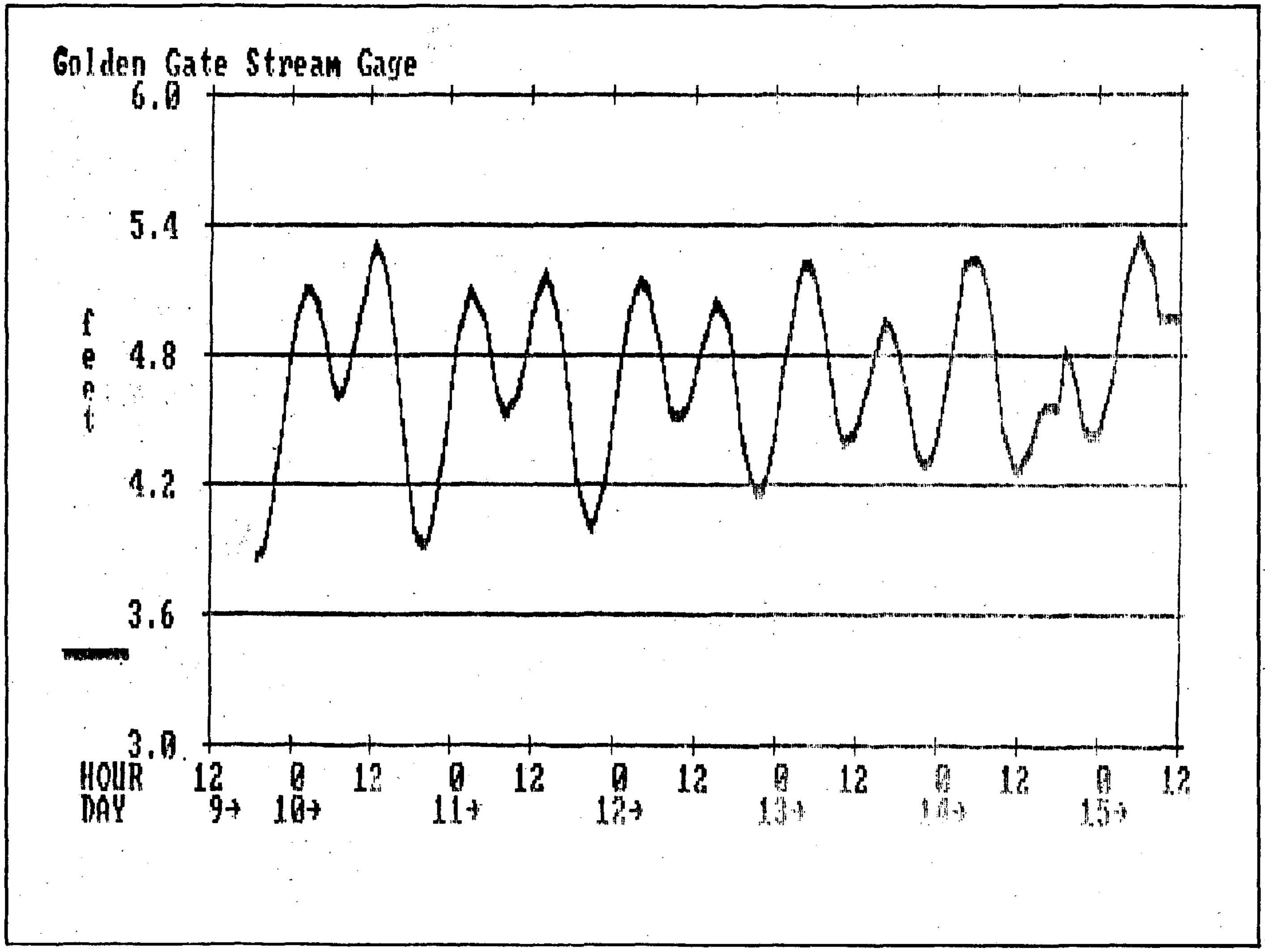


FIGURE 4.9: Sample Display from Tidal Gage in San Francisco Bay; ALERT Type Network

RESEARCH PROJECTS

Other real-time tide, storm surge and wave measurement programs are in operation. Two major projects are described below.

West Coast Wave Measurement Network The COE and the California Department of Boating and Waterways have funded a Coastal Data Information Program for the collection of wave data along the west coast of the U.S. The system was designed and is operated by the Scripps Institute of Oceanography (SIO). The primary purpose of the program is to improve understanding of the wave climate along the west coast. Knowledge of the wave climate helps with understanding the potential for sediment transport and coastal erosion, which are of major concern on the west coast. Major users of the information are SIO, the COE, coastal engineers, and more recently the NWS and U.S. Navy.

The complete network consists of about 20 gages, including wave buoys and wave directional stations in deep water and pressure gages near shore. The near shore sites use bottom mounted strain gage pressure sensors. Data from each gage are telemetered to a field station (by VHF radio from deep water wave buoys, and by cable from near shore pressure gages), where time series wave data are stored in a buffer. At preset intervals, the central station computer at Scripps calls up the field stations, receives data from the buffer, performs validity checks, analyses the data, and stores the data in a databank. During major storms, more frequent measurements can be taken. Data are available in near real-time to all system subscribers, who may access the system using a microcomputer or terminal and a modem. Historical data are also available on-line. Raw data are stored by the COE, Coastal Engineering Research Center (CERC) office in Vicksburg, Mississippi.

Data on significant wave length and period (wave spectral data is not sent) are transmitted from the SIO central station computer by telephone lines to the NWS computer in San Diego. There the data are entered into the NWS AFOS system (Automation of Field Operations and Service), transmitted to the NMC in Silver Springs, Maryland, and then sent back out over the AFOS system every three hours to NWS offices in California, Oregon and Washington. These NWS offices use the data in preparing forecasts and to report actual surge and wave conditions in their routine weather bulletins released over NOAA weather radio. This information is apparently very useful for fishermen and other mariners. The NWS reports that it has had good success in obtaining and using data from the SIO network. Even when the NWS AFOS system is temporarily down, the NWS can call into the SIO computer system using an IBM PC microcomputer. Recently the U.S. Navy has begun using the SIO network as part of a tsunami warning system.

In addition to the west coast network, the SIO system includes one station at the COE, CERC research station at Duck, North Carolina. SIO personnel indicated that they are interested in adding other stations to their network, possibly including a future Connecticut network of storm surge and wave gages. Data from the local stations would be input to the SIO computer, analyzed and them sent back out to the local area. Only a terminal and modem are needed to connect with the SIO system. SIO charges private users a subscription for participating in the system, and would make it available to a government user with an appropriate contribution (the State of California presently contributes $50,000/year, and is expected to increase their support to $100,000/-year). SIO could also assist with installation of gages and telemetry. SIO publishes a monthly and annual report which summarize the data collected by the system. A subscription costs $95.00/year. (115,135,136,137,138,175)

Florida Monitoring Network The University of Florida at Gainsville, in cooperation with the COE, CERC has developed a coastal storm surge and wave monitoring system off the Florida coast. This system is designed to collect data for engineering design and research purposes, and is not used for forecasting storms or surge. A network of approximately nine pressure transducer gages is installed on the ocean bottom at a depth of about 10 meters around the Florida coast, approximately one-half mile offshore. Under normal conditions, the system transmits data via underwater telephone cable to the receiving unit at the University. During major storms, the system (two-way communications) is switched to an internal mode, and data are recorded on tape stored within the gages. (158,159,160,161,162)

4.3.3 Long Island Sound Water Quality Program

The State of Connecticut recently began work on a new program to investigate water quality and marine living resources in Long Island Sound. Efforts will be focused on the western part of the Sound, where sewage effluent and other pollutants from New York City enter LIS through the East River. The program is expected to include long term monitoring of nutrient input, productivity, and circulation, which may involve tide and current meters at selected areas in LIS. At a recent workshop, participants suggested that a two-dimensional, vertically integrated, numerical circulation model of the Sound be developed. Development costs for the model were estimated at more than $500,000. Start-up funding may be available in FY 1987. (177,178,179)

5.0: FLOOD MONITORING NETWORK DESIGNS

This section describes the general design of four different flood monitoring networks. Each network design provides a different degree of compatibility with the Connecticut ASERT system, as well as variations in the type and quality of data to be collected. Variations and enhancements to each network design are also indicated. The final choice of a preferred network design depends upon a number of factors, including: State budget, funding levels for federal programs directly related to flood monitoring and warning; how dependent the State network should be on other federal, state or private programs; and user needs to be met.

5.1 DESIGN CRITERIA

An optimal flood monitoring network would possess the following characteristics.

(1) Accurate measurement of tides, storm surge, and wave spectral characteristics.
(2) Sufficient number and placement of stations to measure all significant variation in tide, storm surge and wave action along the CT coast.
(3) Accurate measurement of wind speed, wind direction, and barometric pressure at each gage station.
(4) High reliablility, including continued operation under severe storm conditions.
(5) Ability to increase sampling frequency during storms, or at other times as needed, from the central receiving station.
(6) Data available in real- or near real-time to potential users, including State emergency officials, municipal officials, NWS, navigation interests, and researchers.
(7) Audible alarms when storm surge and wave conditions exceed critical levels.
(8) Processing and display of data to permit easy interpretation and use.
(9) Archiving of data for research and verification purposes.
(10) Low equipment and installation costs.
(11) Low maintenance costs, including long life for equipment.
(12) Fully compatible with ASERT.

No single network design appears to meet all of these criteria. In the following sections, several network designs are presented, each of which requires some compromise on one or more of the criteria.

5.2 NUMBER AND LOCATION OF GAGES

5.2.1 Tides and Storm Surge

To measure tidal action and storm surge affecting coastal communities, gages should be placed at a near-shore location, outside the breaker zone. Although tides and storm surge are affected by shoreline configuration and the presence of manmade and natural obstacles, this affect in LIS is relatively small. (6,7,46) Therefore, gages may be placed along the open coast or within a protected harbor with confidence that the measured tide and surge will not vary greatly from nearby locations.

No projected storm surge data from numerical models is available for the Connecticut coast to provide guidance for placement of storm surge gages along the coastline[1]. Therefore, empirical data gathered from storm surge observations and statistical studies of storm surge must be used to suggest the placement of gages. These data indicate that a reasonable measurement of storm surge along the Connecticut can be obtained by locating gages in five areas.

(1) Stonington to New London: Storm surge decreases from Stonington to New London where it reaches a local minimum. The large amplification of storm surge in the Thames River also makes this area important for measurement.

(2) Waterford to East Haven: This reach has an almost constant upward slope in storm surge from east to west. A point about midway along this reach should permit determination of surge along the entire area.

(3) New Haven area: A local maximum in storm surge occurs in the area of New Haven, and should be measured.

(4) Milford to Bridgeport: A significant and rapid decrease in storm surge levels occurs in this area. It is also the lowest point for storm surge along the Connecticut coast.

(5) Greenwich/Stamford area: Storm surge is largest in western Connecticut, and this is also an area with complex offshore bathymetry and offshore

[1]The NWS SLOSH storm surge model is now operational, but projected storm surges from theoretical hurricanes have not yet been prepared. Storm surge estimates for the Connecticut coast prepared during Hurricane Gloria were not available from the NWS for this study. There are no other operational storm surge models that cover the entire Connecticut coast.

islands.

Measurement of storm surge at these five areas should permit a reasonable estimation of storm surge at other coastal areas. However, the choice of these five areas is based on historical statistical studies that minimizes local variations and differences associated with individual storms. To determine just how extensive local variations in storm surge may be, it is suggested that, in addition to establishing permanent measurement stations at these five sites, additional gages be placed at critical points along the coast for temporary periods. These temporary stations can be used to correlate storm surge at intermediate locations with adjacent permanent stations[2]. To account for seasonal variations, these temporary stations should remain in place at least one year.

5.2.2 Waves

Two major options are available for the placement of wave gages:

(1) Wave gages may be placed in deep water offshore, beyond the zone of major shoaling. Data from offshore gages, although not specific to any single location, can then used in a wave model (including wave refraction, diffraction, reflection) to obtain wave estimates closer to shore. As discussed in Appendix B, the ability of models to shoal waves accurately is limited, and if the wave data are sufficiently far offshore that wave generation continues between the gaging site and the shore location, the shoaled wave estimates will be incorrect. The primary advantage of offshore gages is that a few gages can be used as representative of a large section of coastline.

(2) Wave gages can be placed very close to shore, such that the waves measured are those that impinge directly onto the shoreline. The advantage is that accurate, site-specific information is available for the local shoreline. The disadvantage is that the wave data cannot be used for adjacent coastal sites, without expensive and often inaccurate modeling efforts which estimate offshore waves from the inshore measurements, then shoaling of these offshore waves into the candidate site.

---

[2]This would be similar to NOS procedures of placing temporary, subordinate, tidal stations at many points along the coast to establish tidal correlations with its two permanent tidal stations in Connecticut.

Because waves in much of LIS are primarily generated by local winds rather than offshore swells, and the need for site-specific data, near-shore gage stations are suggested, even though the wave data may not always be used to estimate wave action at ungaged, nearby locations.

From a theoretical standpoint, there is no single optimum spacing of wave gages along the Connecticut shoreline. Waves will develop differently in LIS, depending on the wind speed, direction, and orientation of the coastline. For instance, winds moving along the maximum east-west fetch of LIS will exhibit large alongshore gradients in the spectral wave characteristics, i.e., wave height and peak wave period will grow continuously with distance down the Sound. Local effects such as sheltering by offshore islands, or refraction by shoals, will cause significant local variability. This sheltering and refraction will affect different parts and lengths of the coast according to wind speed and wind direction.

Optimally, some guidance in locating gage stations would come from previous studies of waves within LIS, either in situ measurements or numerical modeling. As is typical for much of the east coast of the United States, little direct measurement of waves has been made in LIS, and no comprehensive, long-term monitoring gage records exist. Most records are very short, and of uncertain quality, and do not warrant use in setting the spacing and location of wave stations.

Visual observations of waves have been made at a number of locations along the coast of Connecticut as part of the Beach Erosion Project established following the Ash Wednesday storm of 1962 (181). These data are of questionable quality, since visual observations are known to be biased and inexact. Although these data were examined to try to establish a sound basis for locating gages, this effort proved unsuccessful.

Calculation of wave development in LIS using empirical hindcast techniques suggests that at a minimum three wave gages should be located along the shore. In the eastern part of the Sound, waves are nearly those of the more open coastal waters of the Atlantic. Further west, in the middle regions of LIS, the waves become more typical of a sheltered embayment, while to the far west, the waves are almost entirely shallow-water, locally generated waves.

The combination of the alongshore gradients in wave action and the complex nearshore bathymetry results in a recommendation to place three permanent wave gages along the Connecticut shoreline.

(1) Eastern Connecticut. One gage should be located in the eastern part of the sound, along a section of shoreline exposed to both locally-generated waves and more distantly generated ocean swell (but outside the immediate influence of Fisher's Island.

(2) Mid-State. Another gage is suggested near mid-state, offshore of New Haven. Waves in this area are predominantly locally generated within the Sound, having a large fetch during both westerly and easterly winds. Although somewhat sheltered from westerly winds by the shoals off Bridgeport, it is exposed fully to the brunt of an easterly wind.

(3) Western Connecticut. Another gage should be located near Stamford or Greenwich. This location is representative of much of the western part of the State, with its crenulated shoreline, and variable offshore bathymetry. This area is subject to only a minor westerly fetch, but the long easterly fetch could potentially generate large waves.

Because of local topography and offshore islands, these three sites will not be representative of all shore points. For example, they will not permit determination of wave action in Fisher's Island Sound. Because the communities in this reach of coastline (Stonington, Groton, New London, Waterford, and East Lyme) have few structures in the V-Zone (refer to Table 2.4), absence of a wave gage here is not critical. A permanent gage can be added in this area later if needed. To determine if additional permanent gages are needed and to attempt statistical correlation of wave behavior between the sites with permanent gages and nearby ungaged sites, it is recommended that two additional wave gages be used to temporarily measure sites at various locations along the coast. Because wave climate during a variety of weather conditions is desired, and to reduce installation and removal costs, it is recommended that the roving wave gage stations remain at each temporary location for at least two years.

5.3 ALTERNATIVE NETWORK DESIGNS

Based on the design criteria given in Section 5.1 and the recommendations for number and location of gages in Section 5.2, this section describes several alternative network designs. Network designs which are ASERT compatible are presented, as required by the initial study objectives. However, since these designs must either omit or compromise wave data (or compromise reliability of the ASERT system), other network designs are also presented. One set of alternatives involves a wave network separate from the ASERT compatible storm surge network. Another alternative describes a network totally independent of ASERT. The major alternative network designs, with possible variations on each, are described below and summarized in Table 5.1.

5.3.1 Cautions on Cost Estimates

Cost estimates for equipment, software development and installation are provided for each alternative described. These estimates must be used with great caution. Although several vendors were contacted for cost estimates, most were reluctant to provide estimates without a detailed set of specifications. Those estimates provided by vendors were not always comparable because they made varying assumptions regarding instrumentation needs. Some vendors provided estimates for a complete monitoring network, while others provided only costs of individual components. Costs of similar equipment can vary greatly depending upon quality and design standards. The equipment cost estimates in this report were developed by the contractor based on information provided by vendors and past experience with vendors and equipment at WHOI and elsewhere. The estimates should be considered more as relative values than as absolute cost estimates.

Similarily, cost estimates for installation are approximate, and should be considered relative rather than absolute. Installation costs do not include surveying to establish reference elevations.

5.3.2 Tide and Storm Surge Measurements: (ASERT Compatible Network)

GENERAL DESCRIPTION An ASERT compatible network that measures tidal movement and storm surge can be established that relies heavily on use of existing recording tide stations.

ALTERNATIVE NETWORK DESIGNS	ASERT COMPATIBILITY	GAGE STATIONS	TYPE OF GAGE	APPROXIMATE COST
1. TIDE AND STORM SURGE (ASERT Compatible)		Existing stations at New London, Old Saybrook, Bridgeport, and Stamford. New Station at New Haven. Two roving stations		
1-a Maximum Use of Existing Instrumentation	Fully Compatible		Existing gages fitted with interface. Strain gage pressure sensor at New Haven and roving stations.	51,000
1-b Upgraded Instrumentation	Fully Compatible		Strain gage pressure sensor or NOS gage	58,500
2. TIDE, STORM SURGE AND WAVE MEASUREMENTS (ASERT Compatible)		Same as Alternative 1 except for a new station at Stamford Harbor Breakwater to replace existing Stamford Harbor gage, and relocation of Old Saybrook gage site to open water side of breakwater.	Top-of-the-line strain gage pressure sensor or quartz pressure sensor.	
2-a Simplified Wave Data	Some wave data may be lost due to interference			100,000
2-b Field Station Processing of Spectral Wave Data				
2-b.1 Transmittal of processed spectral data	Higher percentage of wave data loss due to longer transmission time, and overall higher ratio of signal interference			115,000
2-b.2 Store spectral data at field station	Some wave data may be lost due to interference			118,000
3. TIDE, STORM SURGE AND WAVE MEASUREMENTS (Two Networks)	Only 2 stations (Bridgeport and New London) are ASERT compatible. Stations with wave gages are on a separate network	Same as Alternative 2	Top-of-the-line strain gage pressure sensor or quartz pressure sensor.	
3-a One-way Communications				158,000 - 208,000
3-b Two-way Communications				280,000 - 330,000
3-c Linkage to SIO Wave Monitoring System				163,000 - 335.000
4. TIDE, STORM SURGE AND WAVE MEASUREMENTS (Independent from ASERT)	Not compatible -- entirely separate system	Same as Alternative 2	Quartz pressure sensor	440,000

TABLE 5.1: Summary of Alternative Network Designs

<u>Station Locations</u> For this network, five permanent and two temporary "roving" stations are recommended (Figure 5.1).

EXISTING STATIONS

(1) NOS station in the Thames River at New London.
(2) USGS/DEP station at Saybrook Breakwater at the mouth of the Connecticut River.
(3) NOS station in Bridgeport Harbor.
(4) COE/USGS station in Stamford Harbor.

NEW STATION

(5) New Haven Harbor. A new station would be located at the West Breakwater at the entrance to New Haven Harbor.

ROVING STATIONS

(6) At sites to be selected
(7) At sites to be selected

<u>Station Description</u> Each station would be equipped with water level and meteorological sensors (wind speed and direction; barometric pressure). Water level (stillwater) would be determined and transmitted at 5, 6, or 15 minute intervals[3], and meteorological data would be transmitted on an event basis. Each station would be equipped with ASERT compatible encoding and radio transmission instruments.

At the four existing stations, the transmitter and other instrumentation would be located within the existing instrument housing (NOS instrument housing at New London and Bridgeport; Coast Guard lighthouse at Old Saybrook; and COE Hurricane Barrier offices at Stamford). For the new station at New Haven Harbor, instrumentation would be housed in a Coast Guard lighthouse tower located on the breakwater. The antenna and meteorological instrumentation could be mounted to the tower. Commercial power is available.

---

[3] A measurement frequency of once every six minutes (10/hour; 125/tidal cycle) would be compatible with NOS stations. A measurement frequency of once every 15 minutes (4/hour; 60/tidal cycle) would be compatible with the USGS maintained stations. Existing USGS equipment would permit sampling frequency at the USGS stations to be increased to every five minutes (12/hour; 150/tidal cycle) (38), which would permit improved graphic display of tide levels.

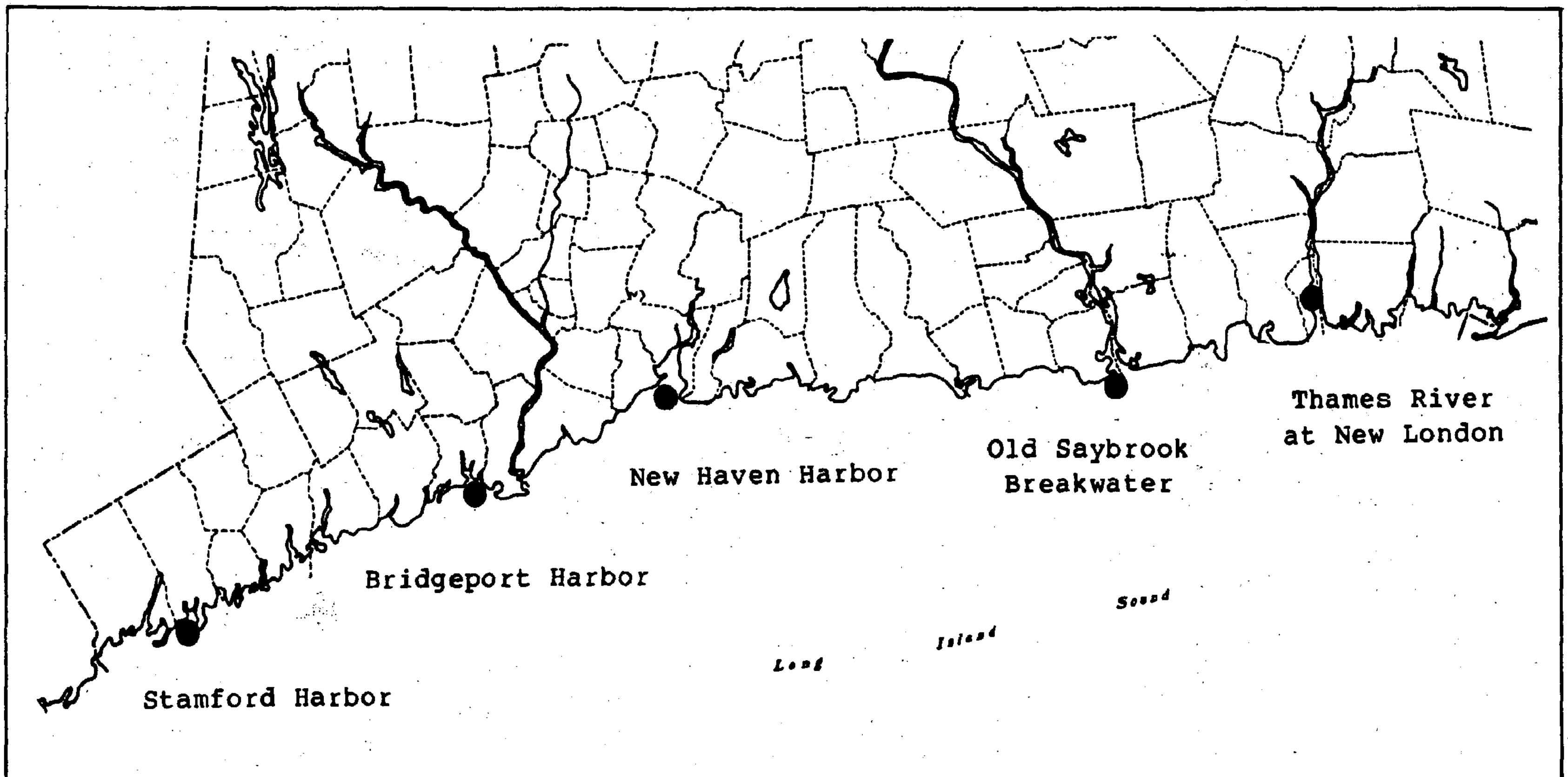


FIGURE 5.1: Locations of Permanent Gage Stations for Tide and Storm Surge Measurements

A good quality strain gage pressure sensor is recommended for water level measurements[4]. The pressure sensor would be placed on the ocean bottom, approximately 100 feet beyond the south edge of the breakwater. The suggested mounting for the sensor is a steel pipe tripod, with concrete weights. Cable from the sensor should be buried in the sediment and secured against the breakwater. (182,183) Figure 5.2 illustrates a typical installation.

Data Transmission and Processing Data would be telemetered by VHF radio to the existing base stations in Hartford and Bloomfield. It is anticipated that radio signals from all stations could reach the base stations with existing ASERT repeaters, as shown in Figure 5.3[5]. New repeaters would be installed if required to get a signal through to the base stations.

Received data could be processed by the existing Enhanced ALERT software (61). Stillwater levels could be treated similar to stream level data[6]. It is recommended, however, that a new software module be developed for the Enhanced ALERT software to process the tide and storm surge data. This module would include predicted tide levels for each station using NOS data (Stamford, Bridgeport and New London) or NOS procedures for determining tide levels (Old Saybrook and New Haven stations) by correlation with the New London or Bridgeport stations. Programming should include triggering an audible alarm whenever actual water levels exceed predicted tide levels by a specified amount (such as one or two feet). A graphic display, as well as tabulations, of predicted vs. actual water levels should also be included. Costs of developing this module are estimated at $5,000 to $10,000 (assume $8,000). Archiving of processed data would depend on procedures developed for archiving data from the ASERT system. These procedures have not yet been finalized (184).

---

[4] The accuracy required from a top-of-the-line strain gage pressure sensor or quartz pressure sensor is not essential for stations used to measure only tide and storm surge.

[5] This configuration for signal transmission is based on information from topographic maps. No field checks have been made to confirm signal transmission.

[6] See for example, Figure 4.9, which is a printout of water level data from a tide gage in San Francisco Bay, prepared with the Enhanced ALERT software (61).

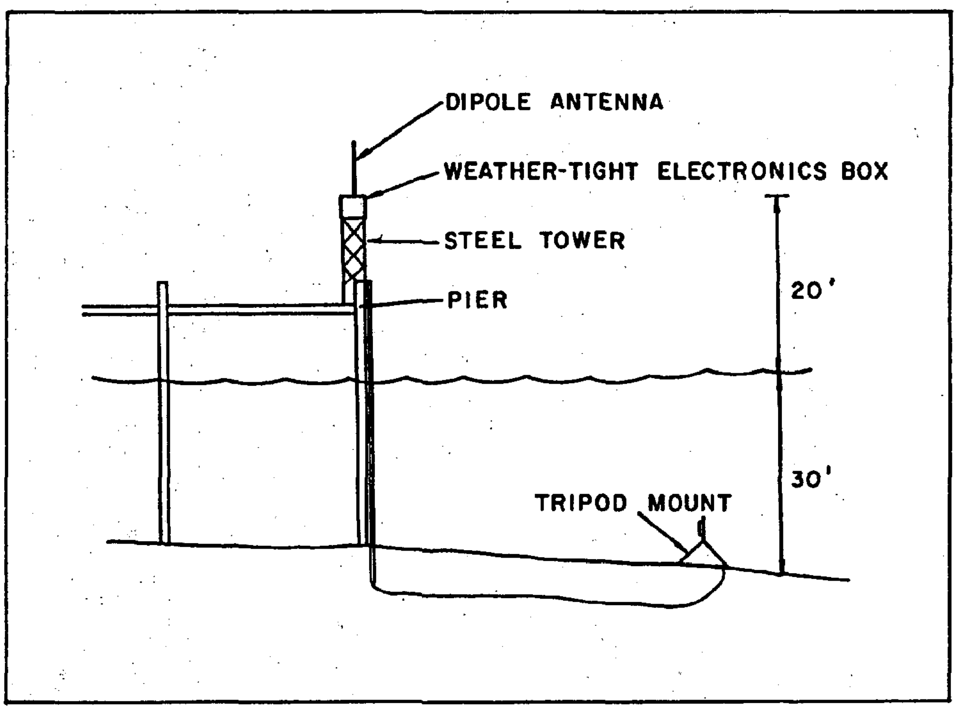


FIGURE 5.2: Typical Gage Station Installation

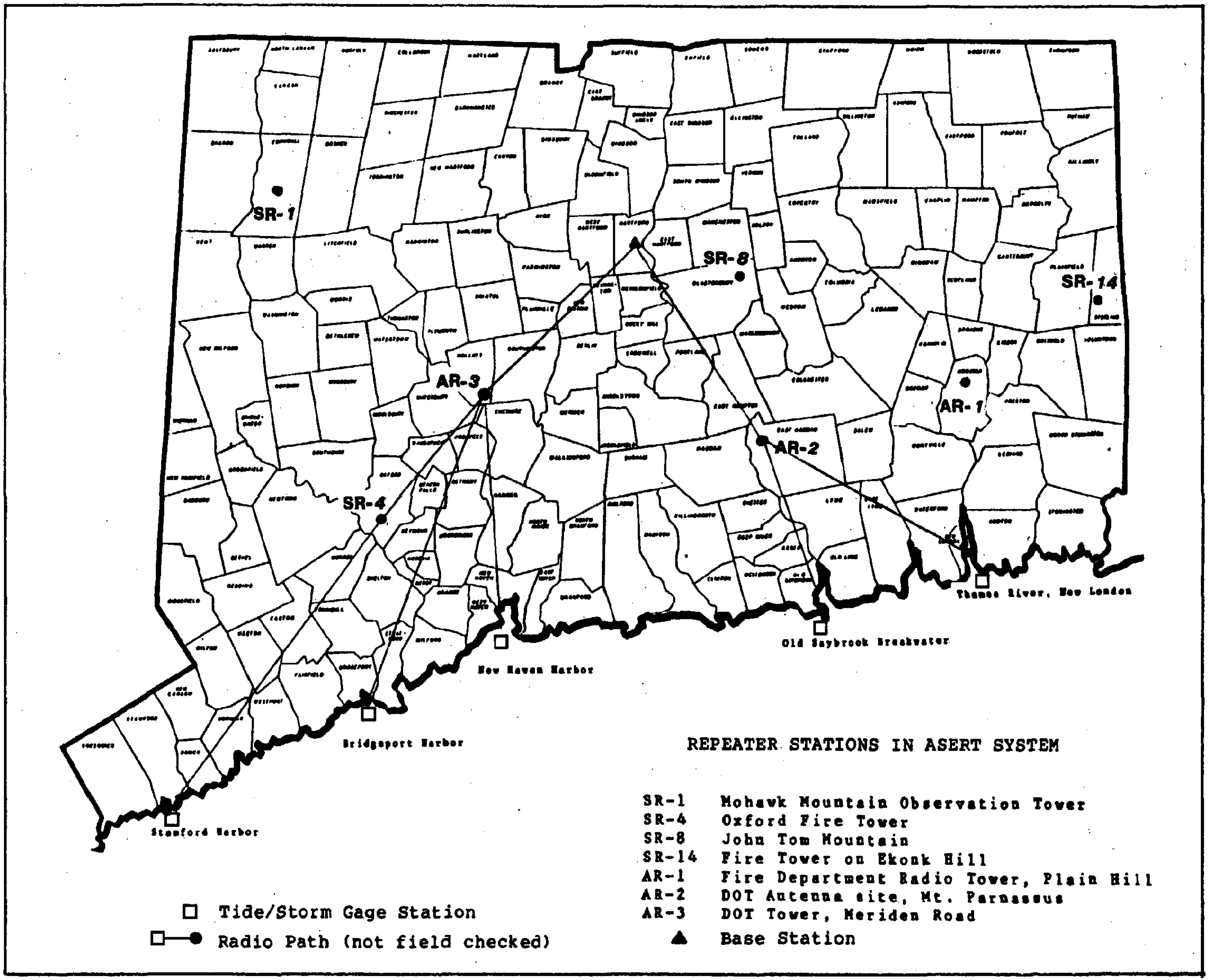


FIGURE 5.3: Radio Telemetry Network

ALTERNATIVE DESIGNS

Maximum Use of Existing Instrumentation: Alternative 1-a One alternative maximizes the use of existing instrumentation at the four recording tide stations which would be incorporated in the system. Presently, these stations employ either bubbler gages or float gages. These same gages could continue to be used by installing a mechanical drive to interface the gage with an ASERT compatible transmitter. The new gage station at New Haven Harbor and the two roving gages would employ a pressure transducer gage as recommended above. These gages would require an analog connector to an ASERT compatible transmitter (176).

Equipment costs for existing stations are estimated at approximately $5,000 each, including interface units, transmitter, back-up power supply, cable and antenna, and meteorological sensors with conditioning electronics and cable. Costs for new stations (permanent and roving[7]) are estimated at approximately $6,500 each, including the above equipment plus a pressure gage, gage mounting, and underwater cable. Total equipment cost for the 5 permanent and 2 roving gage stations in this option is approximately $39,500. Including software costs, the total equipment cost of this option is approximately $47,500. Installation costs would be approximately $3,500.

Upgraded Instrumentation: Alternative 1-b A second alternative is to replace the existing water level sensors with new pressure transducers[8]. Each station would be equivalent to the new stations described in Alternative 1-a, with equipment costs of about $6,500/ station, and a total equipment cost for the seven stations of about $45,500. Including software, total equipment cost

---

[7] Does not include costs of instrument housing for roving stations, since the location of these gage stations has not been selected and the possible availability of existing instrument housing is unknown.

[8] Replacement of existing equipment will require approvals and coordination with the agencies that own the tide stations. Agreements will have to be reached with NOS for the New London and Bridgeport gages, COE and USGS for the Stamford gage, and USGS for the gage at Old Saybrook. Agreements will also have to be reached with these same agencies for adding interfaces to the existing gages, and adding the additional meteorological and transmitting equipment.

of this alternative is about $53,500. Installation is estimated at about $5,000.

5.3.3 Tide, Storm Surge and Wave Measurements: ASERT Compatible

GENERAL NETWORK DESCRIPTION The addition of wave measurements requires modifications to gage station locations, sampling sensors, field station data processing, data transmission, and data processing. This section describes these changes as they would apply to an ASERT compatible network.

Station Locations If wave measurements are added to the monitoring network, a new station must be added at Stamford Harbor (the existing station in Stamford Harbor would be dropped from the network)[9], and the sensor at the Old Saybrook station relocated. The new Stamford station would be located on the West Breakwater at the entrance to Stamford Harbor. Installation would be similar to the New Haven station, utilizing an existing Coast Guard lighthouse tower and mounting a pressure sensor on the ocean bottom off the south (open water) side of the breakwater. (182,183) The Old Saybrook station presently has a bubbler gage located on the protected side of the breakwater (30). The bubbler gage would be replaced[10] with a pressure sensor and relocated to the open water side of the breakwater. Figure 5.4 shows the location of this monitoring network.

Instrumentation Collection of wave data requires a higher quality pressure sensor than is needed for tide and storm surge measurements. A top-of-the-line strain gage pressure sensor or quartz pressure sensor is recommended. Wave data also requires more complex conditioning electronics at the field station in order to handle the burst samplings required for wave spectral data in addition to averaged data for stillwater levels.

To obtain the most complete information, wave directional spectra could also be measured. This would require the installation of wave gage arrays

---

[9] The existing station at the Hurricane Barrier in Stamford Harbor could also be included in the network, but two stations in the same area are not necessary, and for purposes of network design and cost estimating it is not included.

[10] The bubbler gage could be kept in operation if desired.

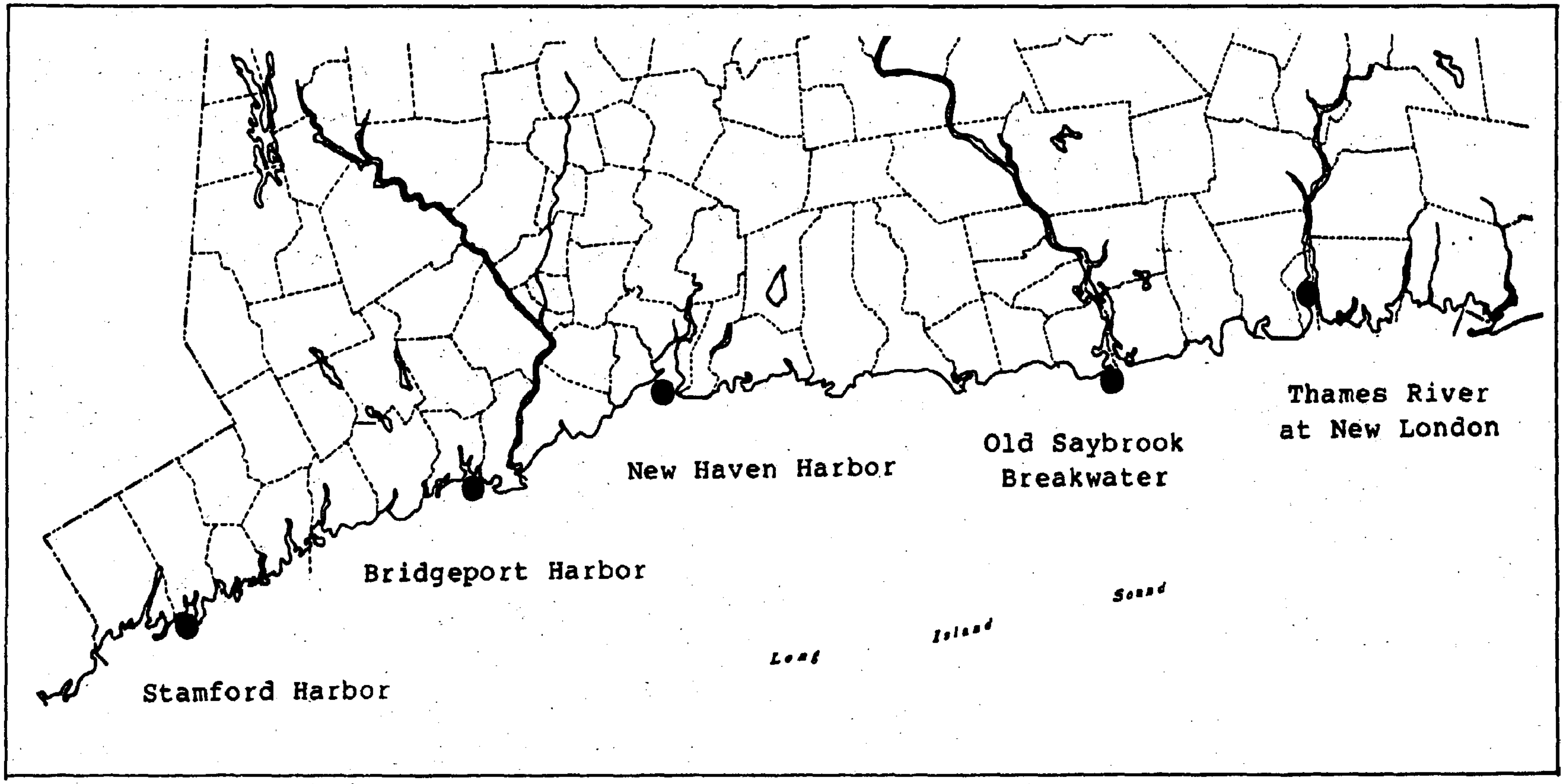


FIGURE 5.4: Locations of Permanent Gage Stations for Tide, Storm Surge and Wave Measurements

(three or four gages at one station) or wave gages with built-in wave direction measurement instrumentation. Because ASERT poses limitations on wave data, the designs for an ASERT compatible wave network assumes wave gages without directional capability.

Data Transmission and Processing The ASERT system was not designed to handle wave information, and there are no existing installations using ASERT/ALERT type systems that collect wave data. Nonetheless, it would be possible to develop a wave monitoring network utilizing the ASERT system, providing certain compromises in data and/or system quality can be tolerated.

The principal limitation of the ASERT system to collecting wave data is the event reporting feature. ASERT/ALERT includes both event and timed reporting. Relative humidity, temperature, and soil moisture are transmitted on a timed basis (currently set at once every six hours). Each relative humidity, temperature, and soil moisture sensor at all field stations is set to transmit at a predetermined time, with each sensor transmitting at a different time to avoid signal interference and loss of data. (67)

Precipitation, streamflow, and wind speed and direction are transmitted on an event basis (data transmitted only when a reading differs from a previous reading by a predetermined value). Because event reported data is transmitted at random times, signal interference may occur at either a repeater station or a base station. Statistically, the short transmission time (about 1/4 second) for each signal will result in very few lost units of data, even for a network with many more sensors that ASERT/ALERT presently has. During storm events, with strong winds, heavy precipitation and rapid increases in streamflow, the number of data units lost due to signal interference may significantly increase. However, signal coding and data processing procedures permit all signals (received or lost) to be accumulated. Therefore, total precipitation and stream level increase can still be determined, as well as the rate of occurrence, and little or no loss of significant data occurs. Similarly, tide and storm surge data would be accumulated, and loss of some individual data units would not be critical.

Wave data presents at least three serious conflicts with the ASERT system. First, any loss of wave spectral data would mean total loss of useful data for that sample. Each sample of wave data is largely independent of others and is not accumulated like rainfall or even storm surge. Second, wave data requires a much longer transmission time than other information on the system. Third, wave data is normally not collected with great frequency (usually only once every 3 to 6 hours), but during storm periods, an increase in frequency of measurement is desirable. ASERT has only one-way communications, making a change in sampling frequency impossible (except by changing at the field site, which is not very practicable).

Any design that adds wave measurements to the ASERT system will require a new software module for the Enhanced ALERT software. Costs for writing this wave module would vary depending on the type of wave data received at the base station and the form of display desired. For cost estimating purposes, a software development cost of $25,000 is assumed.

ALTERNATIVE DESIGNS

Simplified wave data: Alternative 2-a One way to utilize the ASERT system is to collect simplified wave data. Conditioning electronics at gage stations could be programmed to sample waves in a different manner than is normally done. For example, the average wave height and wave period over a given period of time could be mathematically determined. Transmission of this simplified data would require about the same time (less than 1/4 second) as other data transmissions on the ASERT/ALERT system, reducing chances of interference. Loss of a data unit would still mean total loss of wave information for that time period.

Costs for this alternative are estimated at about $10,000/station for a total equipment cost of about $70,000. Including software costs, this alternative would total about $95,000. Installation costs are estimated at about $5,000.

Field station processing of spectral wave data: Alternative 2-b Another procedure (Alternative 2-b.1) for including wave data on the ASERT system would be to collect the full wave spectra data, but instead of transmitting the full data stream, the data could be processed at the field site. Transmital of processed data would require a much shorter transmission time, reducing chances of interference. To verify accuracy of the data, some portion (1/8th) of the raw data should also be transmitted. Because the data would be processed at the field station, raw data would not be archived for research purpose. Data transmissions experiencing interference would still be completely lost, and the transmission time would be longer than other ASERT/ALERT transmissions.

Costs for this alternative would be higher than the previous alternatives due to the more sophisticated electronics required. An estimate of $12,000/station is used for a total equipment cost of about $85,000. Including software development, this alternative would cost about $110,000. Installation costs are estimated at about $5,000.

A variation on this procedure (Alternative 2-b.2) would be to collect full wave spectral data, transmit only significant wave height and significant wave period (along with stillwater level), and store wave spectral data on magnetic tape at the gage station. Several wave measurement systems permit data storage on magnetic tape, and customizing of the conditioning electronics should permit tape storage as well as radio transmission of stillwater level and wave height and period. No information was received on a wave gage collection/storage/transmission unit that performs according to this description, but customizing of existing units should make this configuration possible. Storage of wave spectral data on magnetic tape for periodic retrieval would not adversely affect the flood monitoring network. Spectral data are primarily useful for research and design purposes, which do not normally require real-time data.

Costs for this alternative are estimated at about $15,000/station, for a total equipment cost of about $105,000. Software development should be less since only water level, wave height and wave period will be provided, and is estimated at $8,000, for a total cost of $113,000. Installation costs would also be about $5,000.

Frequent Sampling Rate/Multiple Transmissions: Alternative 2-c Still another procedure to enable wave data to be included on the ASERT system is to increase the sampling rate or to provide multiple transmissions of the same wave sample. Either procedure to reduce the consequences of lost data units creates additional problems by providing unnecessary data for processing and/or archiving, and increasing the number of data transmissions, thereby increasing the overall rate of interference.

Costs should be about the same as Alternative 2-b.1: $85,000 for equipment and $25,000 for software for a total cost of $110,000. Installation costs would be about $5,000.

5.3.4 Tide, Storm Surge and Wave Measurements: Two Networks

Wave data is highly desirable for both flood warning and other purposes, but most alternatives for including wave measurements on the ASERT system require substantial compromises in either the quality of the wave data or the overall reliability of the ASERT system. Therefore, another alternative was explored that would provide wave data and still be partially compatible with the ASERT system. This alternative requires two separate monitoring networks: an ASERT compatible tide and storm surge network, and a wave network. Three options are presented.

GENERAL NETWORK DESCRIPTION Each option would include an ASERT compatible tide and storm surge network consisting of only two stations: New London and Bridgeport. If these two stations are equipped with pressure sensors, the cost for this portion of each option would be about $13,000, plus $8,000 for software development, for a subtotal of $21,000. The wave network in each option would include permanent stations at Stamford Harbor Breakwater, New Haven Harbor Breakwater, and Old Saybrook Breakwater, and two roving stations.

ALTERNATIVE DESIGNS

One-Way Communications System: Alternative 3-a A separate one-way communications system could be established which would include new repeater stations (possibly at the same sites as ASERT repeaters), a new decoder/receiver unit at the base station, and additional radio frequencies. This separate network would enable transmission of wave data timed to avoid interference among the different gage stations.

Each wave gage station, including pressure sensors with all electronic conditioning to collect water level and wave data, transmitter, antenna, cables, meteorological sensors and backup power supply could range from about $12,000 to more than $30,000 depending upon the specific equipment and whether or not directional wave gages are selected. Repeaters for this system could range between $7,000 and $11,000, and a receiver/decoder would be approximately $6,000. For comparative purposes (assuming three repeaters are needed), assume a cost of $130,000 for non-directional wave stations and $180,000 for directional wave stations (directional gages; not arrays). The total for both networks (surge and wave) would range from about $150,000 to $200,000. Installation costs are estimated at about $8,000.

<u>Two-Way Communications System: Alternative 3-b</u> Installation of a two-way communications system would permit operators at the central receiving station to reprogram wave gages to increase or decrease sampling frequency as desired. This would permit maximum utilization of the wave network during storms. Costs for this wave network could range from about $250,000 for non-directional wave stations to $300,000 for wave directional stations (directional gages; not arrays). The total for both networks would range from about $270,000 to $320,000. Installations costs are estimated at about $10,000. The total for both networks could be as much as $340,000.

<u>Linkage to SIO Wave Monitoring System: Alternative 3-c</u> Another alternative is for the State of Connecticut not to process wave data itself, but to tie into the SIO wave data collection network. To establish the linkage with SIO, wave data would be transmitted over a separate communications system (as with Alternatives 3-a and 3-b) to the Hartford base station. Received data would be routed to a microcomputer (or other microprocessor unit with buffer memory sufficent to temporarily store data from all wave stations) which is linked by modem to a dedicated phone line. At preset times, the SIO computer would initiate a telephone call to the Hartford base station to receive the most recent data from each wave station and initiate data processing. Data on significant wave height, significant wave period and wave spectra would be available to Connecticut users in a few minutes by calling

the SIO computer via a modem connection. Processed data would be published monthly by SIO, and additional data processing performed and published annually (See Figures 5.5 and 5.6).

Although it was not specifically investigated, it is probably feasible to use the existing ASERT computer and a new module to the enhanced ALERT software to store data for SIO processing. Presumably, the software module could also extract water level, significant wave height and significant wave period data for immediate input into the ASERT system, while passing spectral data on to the SIO computer for processing. Equipment costs would be about the same as the two previous alternatives, depending upon choice of one-way or two-way communications, directional wave gages and other variations in equipment type and quality:

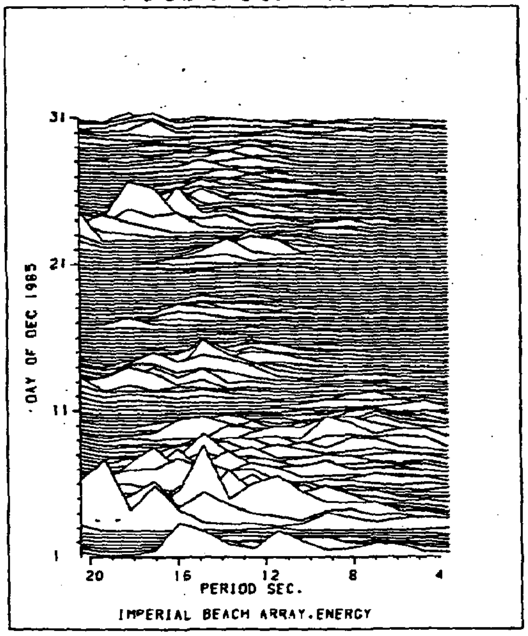
- One-way communications, non-directional wave stations: $130,000
- One-way communications, directional wave stations: $180,000
- Two-way communications, non-directional wave stations: $250,000
- Two-way communications, directional wave stations: $300,000

Software development costs are assumed to be about $25,000, and installation costs would range from about $8,000 to $10,000 depending upon whether one-way or two-way communications were used.

The principal advantage to joining the SIO network is the cost savings from having all data processing and archiving handled by SIO (and not having to develop specialized software, if that option is chosen). The annual savings in data processing and archiving could be substantial. Another advantage to the SIO network is that wave data could be easily input to the NWS AFOS system for distribution to the New York WSFO, Bridgeport and Hartford WSOs, and other appropriate NWS offices.

There are, however, some distinct disadvantages to utilizing the SIO network. Data must be input and retrieved from the SIO computer system through telephone lines and modem links, making it somewhat more susceptible to disruption during storms (both California and Connecticut storms) than a radio based system. A major limitation of the SIO system is that water level (tide and storm surge) is not routinely processed and reported by the system (ASERT software enhancements may overcome this limitation). Other disadvantages include dependence upon another organization for maintaining a significant portion of the total network;

WAVE ENERGY SPECTRA DEC 1985



IMPERIAL BEACH ARRAY.DIRECTION
DEC 1985

ANGULAR DISTRIBUTION IN PERIOD BANDS
(ANGLES IN DEGREES)
BAND PERIOD LIMITS (SECS)

PST DAY	TIME	SIG. AND (DEG)	TOT. SXY (CM. SQ)	22-18	18-16	16-14	14-12	12-10	10-8	8-6	6-4
1	0201	95.1	-237.7	88.1	93.5	95.6	96.9	95.3	95.5	94.5	87.6
1	0801	94.8	-145.9	95.6	91.0	92.0	95.4	94.6	96.1	97.7	91.0
1	1401	93.7	-98.8	91.4	94.2	92.7	92.5	95.7	93.6	93.3	94.9
1	2001	96.0	-64.7	97.0	94.3	94.0	95.5	98.8	96.7	96.2	91.0
2	0201	91.0	-75.8	77.8	92.3	92.9	90.6	85.6	93.7	94.2	88.4
2	0801	91.4	-32.2	96.6	96.8	92.5	91.3	89.7	92.7	93.2	88.2
2	1401	84.6	-29.2	93.1	83.2	91.8	78.3	84.9	87.2	86.4	92.1
2	2001	85.9	-41.4	90.3	91.3	89.2	84.3	83.4	88.8	86.4	36.1
3	0201	93.0	-437.7	92.1	97.0	96.6	91.1	94.5	94.6	88.2	37.2
3	0801	91.9	-475.1	89.1	93.3	94.0	91.6	94.2	90.1	87.4	91.5
3	1401	92.7	-620.1	89.2	93.2	93.4	93.7	92.5	91.3	91.2	93.4
3	2001	92.5	-402.9	83.9	87.2	96.7	90.2	94.7	93.3	91.6	91.9
4	0201	91.9	-300.0	84.8	96.4	92.2	90.8	90.5	92.9	93.0	87.9
4	0801	92.5	-232.6	85.3	89.7	95.6	93.5	91.4	92.3	90.5	87.4
4	1401	93.0	-279.7	74.3	92.7	92.6	93.5	94.0	93.4	88.5	93.9
4	2001	94.8	-152.8	98.5	92.6	94.7	92.4	90.9	102.6	93.3	92.6
5	0201	90.2	-154.7	86.0	94.5	88.5	92.4	88.8	88.7	91.8	92.9
5	0801	92.2	-92.8	84.6	96.0	92.5	92.7	94.4	91.7	88.0	91.4
5	1401	92.3	-139.8	90.9	94.2	92.0	94.1	92.3	93.6	92.5	90.0
5	2004	94.3	-263.3	88.6	96.5	95.0	98.2	91.2	92.0	94.3	94.1
6	0201	95.1	-265.4	92.5	94.8	96.0	94.4	99.6	92.9	95.3	95.1
6	0801	94.1	-240.2	85.3	92.3	93.2	95.4	95.3	92.6	95.3	96.3
6	1401	93.6	-262.7	94.7	94.9	94.4	92.1	91.6	94.6	94.4	95.1
6	2001	93.9	-177.6	95.6	93.6	93.3	95.5	93.8	91.9	95.3	90.7
7	0201	93.5	-126.3	98.3	95.3	92.1	89.7	94.5	92.6	95.7	95.1
7	0801	93.1	-170.8	91.6	95.0	92.4	93.7	92.5	92.7	93.5	94.5
7	1401	93.7	-212.0	88.7	93.9	92.6	96.4	92.3	92.9	94.0	92.7
7	2001	93.2	-236.7	72.3	95.4	94.2	93.3	94.5	91.6	91.7	90.4
8	0201	95.2	-223.7	113.0	95.6	95.6	92.3	94.0	94.5	99.7	95.3
8	0801	95.5	-209.3	97.4	89.6	91.2	94.6	93.3	93.1	98.7	100.3
8	1401	95.7	-241.3	98.7	89.5	93.1	92.0	90.9	95.2	99.9	98.2
8	2001	95.3	-260.4	100.8	94.8	93.2	92.9	94.5	94.4	99.0	94.6
9	0201	96.7	-211.2	92.8	95.8	95.9	94.9	92.6	97.5	99.2	96.6

IMPERIAL BEACH ARRAY.ENERGY
DEC 1985

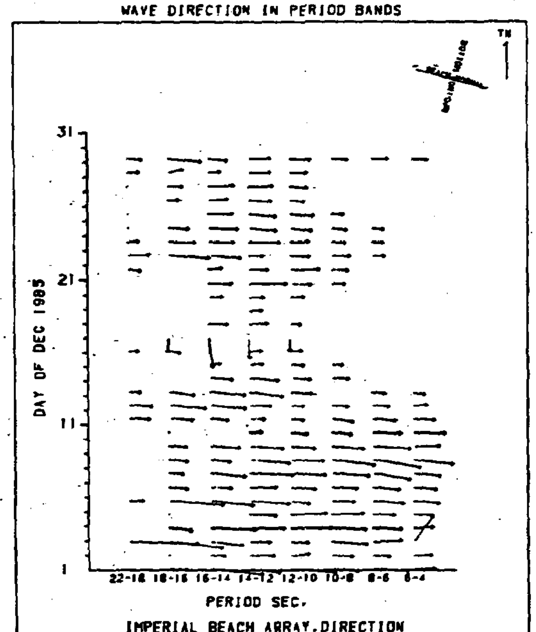
PERSISTENCE
CONSECUTIVE DAYS (1 OR MORE) SIGNIFICANT
WAVE HEIGHT IS -N- METERS OR LESS

METERS	DAYS			
0.5	1.			
1.0	1.	1.	7.	5.
1.5	1.	3.	10.	7.
2.0	2.	28.		
2.5	31.			
3.0	31.			
3.5	31.			
4.0	31.			
4.5	31.			
5.0	31.			
5.5	31.			
6.0	31.			

MAXIMUM DAILY SIGNIFICANT WAVE HEIGHT FOR DEC 1985

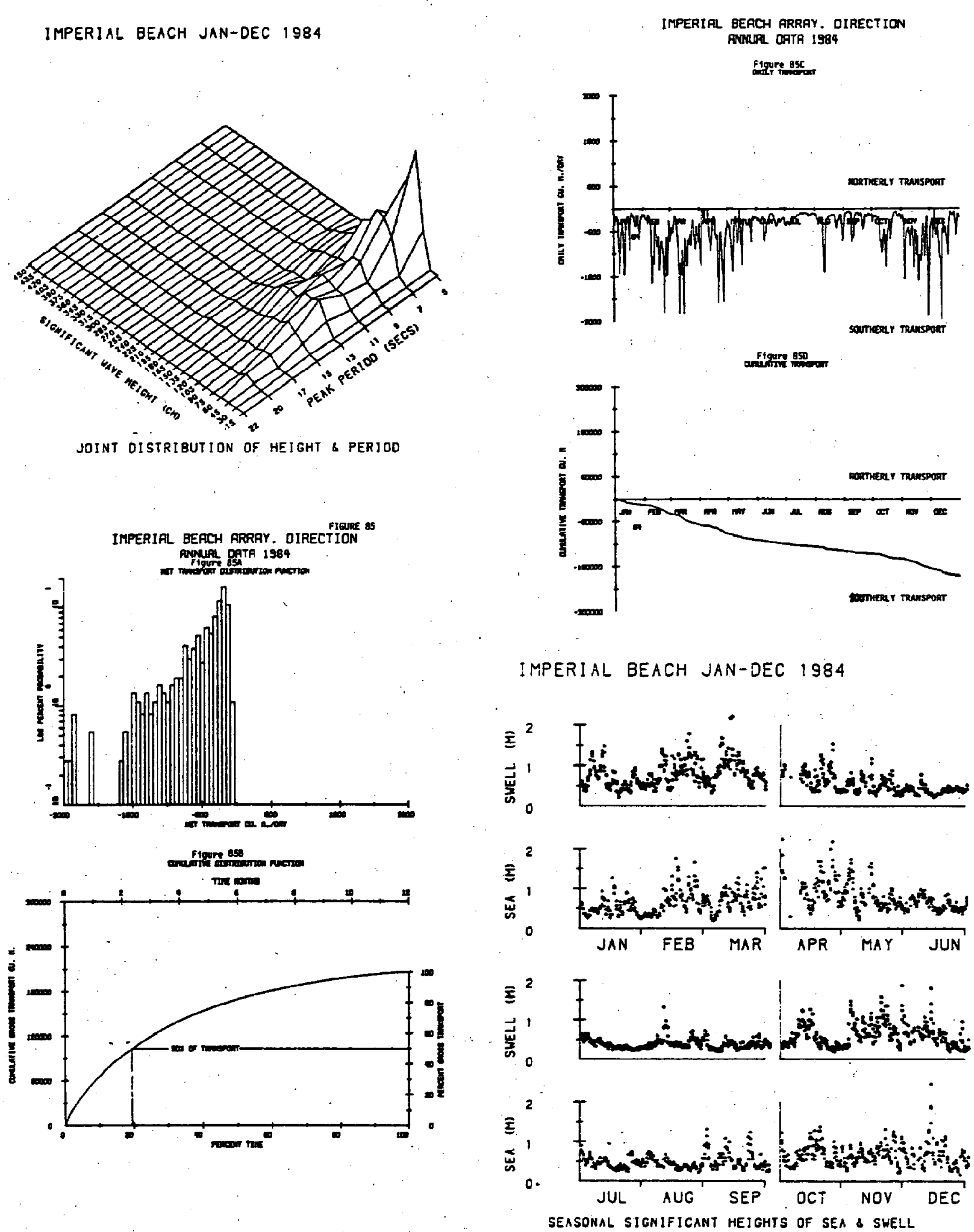
DATE (DEC)	1	2	3	4	5	6	7
SIG. HT (M.)	1.6	0.8	2.4	1.6	1.6	1.7	1.5
DATE (DEC)	8	9	10	11	12	13	14
SIG. HT (M.)	1.8	1.7	1.4	0.9	1.2	1.5	1.2
DATE (DEC)	15	16	17	18	19	20	21
SIG. HT (M.)	0.9	0.5	0.6	0.8	0.5	0.4	0.7
DATE (DEC)	22	23	24	25	26	27	28
SIG. HT (M.)	1.0	1.1	1.6	1.0	0.9	0.8	0.9
DATE (DEC)	29	30	31				
SIG. HT (M.)	0.8	0.9	1.1				

WAVE DIRECTION IN PERIOD BANDS



SOURCE: U.S. Army Corps of Engineers, and California Department of Boating and Waterways. 1986. Coastal Data Information Program, Monthly Report, December 1985. Monthly Summary Report No. 119.

FIGURE 5.5: Examples of Monthly Wave Data; West Coast Wave Measurement Network



SOURCE: Seymour, R.J., et. al. 1985. Coastal Data Information Program, Ninth Annual Report, January 1984 through December 1984. Scripps Institute of Oceanography, La Jolla, CA.

FIGURE 5.6: Examples of Yearly Wave Data; West Coast Wave Measurement Network

access to the data by telephone, including associated telephone charges; and uncertainty over the costs of participating in the network[11].

5.3.5 Tide, Storm Surge and Wave Measurements: Independent from ASERT: Alternative 4

The last alternative presented is for a monitoring network that is entirely independent of ASERT and provides a maximum of information. This network would maintain the same station locations as described for alternatives 2, 3, and 4[12], and use a two-way communications system. Instead of using the ASERT base station computer and software, a separate data processing system would be installed at the base station. Equipment costs for this network are estimated at about $425,000, and installation costs at about $15,000.

5.4 IMPLEMENTATION OF MONITORING NETWORK

5.4.1 Establishment of Gage Stations

Depending upon the monitoring network design chosen, the State has several options and some limitations regarding the sequence and timing of implementation. Because of differences in equipment at existing systems and differences in timing of converting to new equipment, the entire monitoring network probably cannot be installed with its final configuration immediately. The installation may need to proceed over a period of several years in order to coordinate actions and establish interagency agreements with several federal agencies. Some temporary installations may be needed. Following are some suggested

---

[11] Presently, California is the only state making a financial contribution to the SIO network. In recent years California has been contributing $50,000/year and is expected to increase its contribution to $100,000/ year in FY 87. (135) Certainly, Connecticut would not need to contribute this large an amount, but an acceptable amount would have to be worked out between the State and SIO (and probably the COE and State of California).

[12] The NOS stations at New London and Bridgeport could be replaced with stations in the same areas, but in open water to obtain wave measurements along the shore rather than in the Thames River estuary and Bridgeport Harbor. Locations for these new stations have not been identified, and no cost estimates for this alternative were developed.

State actions.

(1) Develop a cooperative agreement with the NOS to have the New London station included in the early group of next generation tide gages to be installed. Assuming that NOS proceeds with a primary acoustic gage and a backup pressure gage[13], arrangements should be made to add the pressure gage to the Connecticut flood monitoring network.

(2) Develop a cooperative agreement with both NOS and NWS to use the NOS gage at Bridgeport Harbor on a temporary basis until NOS upgrades this station with new gages[14].

(3) Develop an agreement with the Coast Guard for continued use of a gage station at the Sayboook Breakwater and new gage stations at the New Haven and Stamford Breakwaters (assuming wave stations are selected).

(4) Modify the existing agreement with USGS for operation and maintenance of the gage station at Old Saybrook to provide for upgrading the sensor (tide/surge or tide/surge/wave), if that option is chosen, as well as maintaining the new wave gage stations at New Haven and Stamford.

(5) If a tide/storm surge only alternative is selected, develop an agreement with the COE and USGS for upgrade and/or use of a gage station at the Stamford Hurricane Barrier.

(6) Hold discussions with coastal communities, DEP Water Compliance Unit, UCONN researchers, and Connecticut DOT, Bureau of Waterways to identify locations that would receive high priority for initial placement of the two roving gages. Proceed with deployment of the two "roving" gages.

5.4.2 Getting Information to Users

Getting tide, storm surge, wave and meteorological data to essential users is just as important as collecting the information. For efficient use of the monitoring network, three user groups need to receive information in real- or near real-time: State emergency officials (OCP and CSP), NWS, and officials of coastal municipalities. Real-time information would be highly desirable for at least two additional groups: Coast Guard and various navigation interests,

[13] There appears to be some uncertainty as to whether NOS will actually install a backup pressure gage. If not, the Connecticut network could utilize the acoustic gage.

[14] It may be necessary or desirable to have the Connecticut monitoring network link directly with the NWS telemetry unit (HANDAR Model 540A).

own base station and associated software, just as communities are presently doing for the ALERT system.

In order for communities to purchase their own base station, costs must be reasonable and the information must be produced in a format that is easy to understand and use. If a double network (tide/storm surge network and wave network) requiring two different communications systems is selected by the State, equipment costs for municipalities will increase; antenna(s) and receiver(s) must be capable of receiving multiple radio frequencies.

NAVIGATION INTERESTS AND OTHER USERS If tide, storm surge and wave data are easily available and reliable, harbor pilots and others involved in shipping could benefit from real-time data from the coastal monitoring network. Navigation users could access the information in several ways:

(1) Installation of a base station at offices of the different harbor pilots associations, marinas, etc. Harbor pilots on ships could contact the association office to obtain current information on water levels and wave heights.

(2) Use of a remote terminal (modem with printout or display) at the pilots offices, marinas and other locations to access data from the Hartford base station by telephone, and relay to shipboard users. If the Hartford base station were equipped with a voice synthesizer, information could be accessed by telephone without need for a remote terminal.

(3) In the near future products should be available to permit shipboard use of a remote terminal (modem with printout or display) or portable computer with modem to access information from the Hartford base station via cellular telephone. Cellular telephone coverage now includes the entire Connecticut coast except the Groton/Stonington area, which should be added during 1986. (180)

5.5 MAINTENANCE PROGRAM

Constant or periodic exposure of equipment to saltwater or saltwater spray promotes rapid corrosion. Equipment can degrade rapidly under these conditions. As a consequence, the coastal flood monitoring network must be maintained with care and diligence.

There are many possibilities for weak links in marine systems, and care must be taken to eliminate these weak links. For example, lack of care in mating cables, or in selection of nuts, bolts, etc., can result in extensive repair costs. Attention to such detail during design and installation can minimize the maintenance requirements of the system. Thus, in accepting any components related to the coastal monitoring network, emphasis must be placed on durability, ability to withstand large waves and high water, and resistance to corrosion. Although a tentative maintenance schedule is presented for consideration with this report, final maintenance procedures will be a function of product reliability, construction techniques, and care during installation.

5.5.1 Maintenance Program

A complete and active maintenance program needs to be developed and rigorously adhered to. It is recommended that one individual be assigned responsibility for the maintenance program. This will provide continuity in the maintenance program, and build familiarity with the system. Similarly, it is recommended that the individual(s) assigned to the maintenance team(s) be given long-term assignments or contracts.

A trouble-shooting sequence should be established by either the State or a contractor, to facilitate rapid isolation of any system modules causing a problem. For example, a procedure should be mapped that will allow discrimination between problems caused at a gaging station, versus those caused at a repeater, versus those caused at a base station. Office tests may help isolate the module at a remote site which is in need of repair, thereby minimizing field testing at remote sites. This type of discrimination is necessary to reduce the time required of field crews, training of field crews in the electronic, communications and mechanical aspects of the system, and to reduce system down time. Spare modules can be purchased to allow rapid correction of problems, with the suspect modules later replaced or repaired.

Inspection teams should accomplish minor repairs (repairs taking less than one hour, not requiring major pieces of equipment, nor requiring special skills) during regular inspections. Each team should have with them a tool and spare parts box with essential equipment needed to accomplish minor repairs.

especially shippers and harbor pilots.

STATE EMERGENCY OFFICIALS The ASERT base station is presently located in the offices of the DEP Water Resources Unit in the State Office Building. The two State Warning Points, OCP and CSP, do not presently have direct access to the ASERT system. To ensure proper coordination among all State emergency officials, local officials and NWS offices during times of potential flooding, it is important that both OCP and CSP have direct access to real-time data on coastal (and riverine) flooding. The radio signals which reach the State Office Building should also reach both OCP and CSP, which are in the same vicinity. Therefore, it is suggested that both OCP and CSP acquire their own base stations.

NATIONAL WEATHER SERVICE The essential NWS stations are the New York WSFO and the Bridgeport and Hartford WSOs. One option would be for each of these offices to install their own base station and receive data directly by radio transmission, just as the NERFC office in Bloomfield now does. However, it may not be possible for the New York WSFO to receive ASERT radio signals from Connecticut due to interference from many other more powerful signals in New York City (185). It would also be highly desirable for the National Meteorological Center in Silver Springs, MD and the National Hurricane Center in Coral Gables, FL to also receive real-time data from the Connecticut coastal monitoring network. To do so, the information needs to be added to the NWS AFOS system, which all of the concerned NWS offices have. The AFOS system is apparently being used to capacity, and specific authorization must be obtained to input additional information to the system. It is also not clear just how ASERT data would be entered into AFOS. (32,36,68,185,186) Clearly, some automated procedure is needed. The most logical entry point appears to be the NERFC in Bloomfield or the Hartford WSO at Bradley Field, Windsor Locks. The State and NWS need to pursue the authorization and procedures for getting ASERT data into the NWS AFOS system.

MUNICIPAL OFFICIALS Municipal officials who wish to use the coastal monitoring network to obtain detailed, geographic specific information on actual storm surge and wave levels must also have direct access to the ASERT system. The most efficient procedure appears to be for local communities to purchase their

For all inspections procedures described below, a written report should be prepared immediately by the maintenance team and submitted to the program manager, including any repairs or maintenance performed by the team and any problems noted that require further attention. The program manager should evaluate these reports and arrange for immediate repair or replacement of equipment, as needed.

5.5.2 Maintenance Schedule

A matrix of maintenance procedures is presented as Table 5.2. Each aspect of the four maintenance procedures is discussed below.

MAINTENANCE PROCEDURE 1 All data should be monitored carefully by the Program Manager to detect any hardware-related problems. Any problems identified can be evaluated more carefully during monthly on-site inspections.

All above-water portions of the system should be inspected visually each month. All hardware should be inspected for structural damage and corrosion. Connectors and mating parts should be verified for stability, and clamping hardware should be checked for tightness and integrity. Corrosion of metal materials must be identified and arrested early to avoid catastrophic failures. If any damage or decay is noted, prompt action should be taken to avoid later failures that could result in extensive down time. Records should be kept to document a history of failures and corroding parts.

The remote backup power supply should be tested at this time. Magnitude of charge and integrity of charging circuitry should be evaluated. If necessary, the battery can be cycled during this inspection.

Clocks should be reset and synchronized, using a portable master clock or radio receiver. A log of clock errors should be kept at each station to permit a history of clock behavior. Excessive drift or decay of the accuracy of the time base can be used to indicate need for clock replacement or modification.

The inspection should be fairly rapid, taking approximately 1.0 to 1.5 hours if no defects are detected. Repairs of any extensive nature might be better made during a return visit, following approval by the Program Manager.

<u>MAINTENANCE PROCEDURE 2</u> Maintenance procedure 2 is a complete visual check and servicing of all underwater components. This maintenance must be done by diving teams familiar with the operation, unless some deployment scheme is devised whereby divers are not required. Divers can initiate inspections from the shore or a small boat, traveling between sites over land.

Crews making these checks of underwater components must be familiar with corrosion problems and common modes of underwater failures. All connectors, penetrators, splices and other fastenings and joints should be inspected. Marine fouling should be removed mechanically, and anti-biofouling paints or coatings should be applied if possible. All zinc anodes should be replaced, and the installation inspected for points of weakness, from both a structural and a corrosion standpoint. Cable condition should be assessed, and the strain relief examined for security. Any breaks, kinks, or other damage to the cable should be noted for proper action.

The extent of scouring and undermining of the underwater mounting should be determined. Is the tripod sinking or scouring, or is the pipe becoming too exposed? The pressure sensor should be inspected, noting corrosion or pitting. Pressure sensor ports should be cleaned, and filled with oil (if applicable). Any problems in these components should be attended to immediately.

<u>MAINTENANCE PROCEDURE 3</u> Maintenance procedure 3 includes a close visual inspection of the electronics at the remote site, measurement of output signal strengths, and general evaluation of all above-water electronic components. Parts with known limited lifetime should be replaced. All antenna fastening and structural bracing should be inspected and replaced if damage or decay is severe. The power backup system should be inspected and serviced completely (water level in batteries adjusted, operation of power back-up should be noted when unit is powered down, then up, and condition of terminals noted before cleaning terminals).

The weather-tight housing should be inspected for weak points or decay. All time-keeping circuits should be reset, and any manufacturer-suggested electronic tests of encoding/decoding and telemetry products should be performed at this time. Signal strength measurements of telemetry power output and receiver sensitivity should be in accordance with manufacturer specifications. Any problems should be tended to immediately.

MAINTENANCE PROCEDURE 4 Maintenance procedure 4 involves complete reconditioning of all underwater components (with the exception of the cable, which should be left buried as long as it is working properly). It should be accomplished from sea on a diver support vessel that has enough enclosed space to refit hardware onto new tripods inside the vessel as it travels to the next site. The vessel must have sufficient lifting capability to retrieve and deploy tripods with instruments. To accomplish this reconditioning, all underwater componenets except cable should be retrieved, and replaced by completely reconditioned components. The tripod or mounting pipe should be replaced by a clean, newly conditioned one with anti-fouling added, the strain termination should be replaced, and the pressure sensor calibrated thoroughly.

At this time a thorough evaluation of the installation and maintenance procedures should be made. Weak points should be identified, and corrected. An evaluation of the long-term potential for decay or corrosion is useful at this point. Should any components be redesigned to allow better performance or wear? Should any element of the maintenance procedure be changed?

5.5.3 Maintenance Costs

The exact maintenance costs will depend upon the specific monitoring network chosen by the State. The cost estimates shown in Tabel 5.3 are only approximations, based on the above maintenance procedures for 7 gage installations, 2 repeaters, and 2 base stations. Only maintenance which directly concerns the electronic components of the monitoring network is included; it does not include activities necessary to maintain the piers, buildings,or grounds that are used as a platform for the network.

TIME BETWEEN MAINTENANCE

STATION	1 Month	1 Year	5 Years
All coastal gage stations	MP-1	MP-2,3	MP 4
Repeaters	MP-1	MP-3	----
Receivers	MP-1	MP-3	----

Note: MP = maintenance procedure, see text. These procedures are suggested to assure high data quality. They should be updated in consultation with the equipment manufacturer and installer.

TABLE 5.2: SAMPLE MAINTENANCE SCHEDULE

Maintenance Procedure	Costs/Month	Costs/Year	Expendable Parts & Equip Per Year	One-Time Equipment
Surface Maintenance				
MP-1	$ 800	$9,600	$ 500(1)	$5,000(2)
MP-3	-	1,600	-	
Underwater Maintenance				
MP-2	-	3,000	500(1)	-
MP-4	-	4,000(3) (20,000/5 years)	600(4) (3,000/5 years)	5,000(5)
TOTALS		$18,200	$4,000	$10,000

(1) Miscellaneous spare parts such as clamps, nuts, bolts, paint, etc.
(2) Field testing equipment
(3) Includes rental of diving vessel
(4) Includes replacement parts and reconditioning of parts
(5) Includes replacement parts such as pressure cases, pressure sensor, etc.

TABLE 5.3: ESTIMATED MAINTENANCE COSTS

6.0: CONCLUSIONS AND RECOMMENDATIONS

Evaluation of the information presented in the previous sections resulted in four general conclusions and related recommendtions regarding the most favorable design for a coastal flood monitoring network and the feasibility of a State forecast and warning system. Each of these general conclusions and recommendatins, along with additional specific conclusions and recommendtions are detailed in this secton.

6.1 EXISTING MONITORING, FORECAST AND WARNING SYSTEMS

o CONCLUSION # 1: The present system of collecting data, preparing forecasts and issuing warnings for coastal storms and flooding is less than optimal.

6.1.1 Planned Improvements to Existing Technology and Programs

One option available to the State is to continue relying upon the existing coastal flood monitoring and warning systems, including improvements to the existing systems and programs that are already underway or planned.

Conclusion # 1a: Planned program changes by several federal agencies should result in gradual and limited improvements to the collection of meteorological and oceanographic data and to issuance of coastal flood forecasts and warnings.

The most relevant of these planned improvements are summarized below[1].

(1) Hurricane Preparedness Studies. NWS, FEMA, and the COE will proceed with their program of Hurricane Preparedness Studies, utilizing results from the SLOSH model. Information on projected storm surge heights and areas to be innundated from different categories of storms should be available for the eastern portions of LIS and the Connecticut shore beginning in 1987, following completion of storm simulations and development of MEOWs for the Narrangansett/Buzzards Bay SLOSH basin. More detailed delineation of storm surge and innundation areas for the entire Connecticut coast should

[1] No attempt has been made in this report to consider the potential impacts of possible major cutbacks in federal program budgets. State officials must consider these possible impacts in making decisions.

be available sometime after 1987 when studies for the New York/Long Island Sound SLOSH basin are completed. Once information for these two SLOSH basins is available, the State and local communities will be able to issue more precise evacuation notices to coastal residents for hurricanes.

(2) NWS Real-Time Data at Selected Tide Stations. The NWS will proceed with its program of temporarily upgrading telemetry at selected NOS tide gage stations, including Bridgeport, CT. Implementation of this program will increase the speed with which storm surge data is received by NWS forecast offices in Silver Springs and New York City, thereby enabling improved forecasts of storm surge for extratropical storms. The availability of this data should also permit an improvement in the establishment of boundary conditions for real-time runs of the SLOSH model.

(3) NOS NGWLMS Program. The NOS will probably proceed with its program of installing a new generation of tide level gages, including the stations at New London and Bridgeport. Eventually, this information will also be available to the NWS to help with improved storm surge forecasts. There is no clear time schedule for installation of the new gages, or for use of the data by the NWS.

6.1.2 Opportunities to Further Enhance Existing Programs

Each of the above programs is likely to proceed without any special effort by the State. However, by being fully aware of these programs and maintaining or establishing communication with the appropriate federal agency offices and individuals, the State may be able to influence somewhat the time at which some program actions are initiated and the degree to which they benefit Connecticut.

Conclusion # 1b: The State can work with federal agencies to maximize the benefits of federal programs for Connecticut and LIS.

o RECOMMENDATION#1:The State should take an active role in working with federal agencies to take maximum advantage of existing programs, and especially program improvements underway or planned.

Recommendation # 1a: The State should indicate to the three federal agencies (NWS, FEMA and COE) involved with Hurricane Preparedness Studies that it desires to have the Hurricane Preparedness Study for the New York/Long Island Sound SLOSH basin initiated as soon as possible. Joint action with the State of New York in requesting a high priority for initiation of this study should be considered.

Recommendation # 1b: State representatives should inquire with appropriate NWS officials regarding the specific schedule for installation of the new NWS telemetry instruments at the Bridgeport WSO, and encourage rapid installation if it has not yet occurred.

RECOMMENDATION # 1c: The State should explore further with NOS the possibility of a cooperative agreement or other arrangement which would permit early installation of one of the next generation tide level gages in Connecticut. The New London gage site would be the most logical choice because of the pending NWS telemetry upgrade at the Bridgeport gage site.

6.1.3 Achievement of State Objectives Through Existing Programs

Conclusion # 1c: Existing systems and programs, even with planned improvements, will not meet all of the State's objectives for better flood warnings and reduced losses.

Reliance upon existing systems and programs to collect coastal flood data and to prepare coastal flood forecasts and warnings will require no extraordinary expenditures by the State, and some improvements over present conditions can be expected, such as:

(1) NWS use of near real-time storm surge data from the two NOS stations in Connecticut (and other locations outside Connecticut) may result in small improvements to:

a. storm surge forecasts for extratropical storms, and
b. storm surge forecasts for hurricanes and tropical storms by providing improved data for establishment of boundary conditions for the SLOSH model.

(2) The development of MEOWs from SLOSH simulations should significantly improve the accuracy of evacuation notices for hurricanes.

(3) The availability of near real-time storm surge data from the two NOS stations in Connecticut could improve the accuracy and timeliness of local evacuation notices for tropical and extratropical storms (if NWS includes actual storm surge elevations in its regular marine weather bulletins and flood warnings).

However, even with scheduled improvements in federal monitoring and forecast/warning programs, not all of the State's objectives may be achieved.

(1) There will be no additional data on wave action, and no improvements in wave forecasts.

(2) The geographic coverage of storm surge data will not be increased: the number of coastal data stations will remain the same.

3) Near real-time storm surge data will be avilable only for two locations: New London and Bridgeport.

6.2 NEW PROGRAMS AND ADDITIONAL IMPROVEMENTS TO EXISTING PROGRAMS

o CONCLUSION # 2: To provide better coastal flood warnings and to reduce flood losses, new programs and substantial improvements to existing programs beyond those already underway or planned — are needed.

Although improvements to all aspects of the present system are certainly possible, not all are equally feasible at the present time, nor will potential improvements in each area yield equal results in reducing flood losses.

Conclusion # 2a: Only limited improvements appear feasible to the existing NWS forecast and warning system for hurricanes and tropical storms. Further, because hurricane warnings are already conservative (i.e. attempt to warn of the most severe likely impact), limited improvements will probably have little effect on reducing flood losses, especially in Connecticut where the coastal flood zone is relatively small.

Conclusion # 2b: Significant improvements appear possible in forecasts of storm surge in LIS due to extratropical storms.

Conclusion # 2c: Significant improvements also appear possible in forecasts of waves in LIS due to extratropical storms and during non-storm conditions.

Conclusion # 2d: Significant improvements in the data base for making storm surge and wave forecasts is feasible.

Conclusion # 2e: Improvements in information needed for local decisionmaking and actions is feasible by supplementing NWS regional forecasts and warnings with more precise real-time information for specific geographic areas.

o RECOMMENDATION#2:The State should initiate actions which will result in improved forecasts and warnings.

Recommendation # 2a: State initiatives should enhance the capabilities of federal agencies to prepare regional forecasts and warning.

Recommendation # 2b: State initiatives should supplement regional federal regional responsibilities with more detailed information in specific geographic areas regarding the extent and timing of anticipated flooding.

Recommendation # 2c: State initiatives should non duplicate federal programs and responsibilities.

Recommendation # 2d: The State should not issue information that conflicts with NWS forecasts and warnings.

6.3 REAL-TIME COASTAL FLOOD MONITORING NETWORK

o CONCLUSION # 3: There would be both immediate and long-term benefits from a real-time coastal flood monitoring network established by the State of Connecticut.

A monitoring network would make possible improvements in coastal flood forecasts and warnings beyond that possible with existing systems, and would provide data important for other uses (see Table 1.1).

o RECOMMENDATION # 3: The State should proceed with development of a real-time coastal flood monitoring network

6.3.1 Type of Monitoring Network

Many alternative monitoring network designs are feasible, each possessing different capabilities and costs.

(1) A monitoring network capable of providing real-time data on tides and storm surge (and meteorological parameters) and that is compatible with the ASERT system is feasible.

(2) Collection of real-time wave data, while providing important information for flood warnings and other uses, would not be totally compatible with the ASERT system.

(3) A monitoring network capable of providing real-time data on tides, storm surge and waves (and meteorological parameters) is feasible, but would be completely independent of ASERT.

(4) Costs for a real-time monitoring network would range from approximately $50,000 for an ASERT compatible network collecting only tide, storm surge and meteorological data, to over $400,000 for an independent network with two-way communications collecting data on tides, storm surge, waves and meteorological parameters.

Recommendation # 3a: If the State determines that low cost and full ASERT compatibility are higher priorities than collection of wave data, it should develop a monitoring network for tide, storm surge, and meteorological parameters with one-way communications, similar to that described in Alternative 1-b

Recommendation # 3b: If the State determines that cost and ASERT compatibility are not major considerations, but complete wave data is important, it should develop a monitoring network for tide, storm surge, wave energy and direction spectra, and meteorological parameters with two-way communications, similar to Alternative 3b or 4.

Recommendation # 3c: If the State desires to balance costs and system performance, it should develop a monitoring network for tide, storm surge, wave energy spectra, and meteorological parameters with one-way communications, similar to Alternative 2b.2.

Recommendation # 3d: Because of the variable quality and type of instrumentation available, persons experiencied in oceanographic and meteorological data collection, transmission and processing should be involved in the final choice of a vendor and contractor for installation.

Recommendation # 3e: The Committee on Automated Flood Warning should work with local communities, the research community, federal agencies, and DEP program offices to identify priority sites for initial installation of the two recommended roving gages.

6.3.2 Use of Data From Real-Time Monitoring Network

Conclusion # 3a: Real-time storm surge, wave, wind, and barometric pressure data from points along the Connecticut coast would enable NWS forecasters to improve both forecasts and bulletins of actual weather conditions.

Conclusion # 3b: Geographically specific and accurate information on actual vs. forecast storm surge and wave heights would permit local officials and residents to make improved decisions and take appropriate and timely actions to protect property from flood losses.

Recommendation # 3f: The State should work with local NWS weather services offices and the NWS Eastern Region Headquarters at Garden City, NY to arrange for data from the monitoring network to be input to the NWS AFOS system.

Recommendation # 3g: A base station should be established in the offices of the two State Warning Points -- Office of Civil Preparedness and Connecticut State Police. These offices should relay data to the Regional OCP offices and municipalities without their own base stations.

Recommendation # 3h: The State should assist local municipalities in setting up their own base stations and properly interpreting data from the monitoring network.

Recommendation # 3i: The State should provide a modem connection or voice synthesizer to a dedicated telephone line(s) to enable users without a complete base station to obtain data on a call-up basis.

6.4 FORECASTS AND WARNINGS FOR STORM SURGE AND WAVES

- <u>CONCLUSION # 4</u>: A State-run coastal flood forecast and warning system -- while technically feasible -- does not offer significant advantages over continued reliance on the NWS.
  <u>Conclusion # 4a</u>: Storm surge and wave height forecasts cannot be accurately developed based solely on a local monitoring network.

  <u>Conclusion # 4b</u>: NWS models and procedures for extratropical storm surge forecasts and wave forecasts are not state-of-the-art and are not designed specifically for LIS.

  <u>Conclusion # 4c</u>: There is no extensive data establishing the accuracy or inaccuracy of NWS forecasts.

  <u>Conclusion # 4d</u>: Complex mathematical models utilizing both local and regional data are needed to accurately forecast storm surge and waves.

  <u>Conclusion # 4e</u>: Development and operation of these models would be expensive -- more expensive for the State than the NWS because NWS already has an operational computerized database.

  <u>Conclusion # 4f</u>: State forecasts, if different from those of NWS, could create confusion and inaction by local officials and residents during emergencies.

- <u>RECOMMENDATION # 4</u>: Instead of developing its own flood forecast system, the State should work closely with the NWS and other federal agencies to improve their ability to provide accurate and timely coastal flood forecasts for Long Island Sound and the Connecticut coast.

  <u>Recommendation # 4a</u>: The State should request that NWS develop a new model for forecasting wave heights in Long Island Sound. This should be a model designed specifically for LIS, accounting for the shallow water conditions and other factors peculiar to LIS. Ideally this model would forecast both open water waves and near shore waves. The model would be utilized by the New York WSFO.

  <u>Recommendation # 4b</u>: The State should request that NWS develop a new model for forecasting storm surge for extratropical storms in LIS. Ideally a numerical model specific to LIS could be developed to replace the empirical model now used by NWS.

  <u>Recommendations # 4c</u>: The State should consider seeking cooperation from Rhode Island and New York State (especially Nassau, Suffolk and Westchester Counties) when requesting NWS to develop new models.

  <u>Recommendation # 4d</u>: The State should work with the New York, Bridgeport and Hartford weather service offices to ensure that, as soon as data from the the Connecticut monitoring network are available to NWS in near real-time, NWS will include the actual as well as forecast storm surge (and wave information if available) in its weather forecasts and warnings for marine and coastal areas.

Recommendations # 4e: The State should also establish a program to monitor, through the monitoring network and observations, actual storm surge and wave heights relative to NWS forecasts. In the event that monitoring of NWS forecasts and warnings should show them to be seriously and consistently inaccurate, then the State could more actively consider developing its own forecast and warning program.

Recommendation # 4f: The State should work closely with FEMA, NHC and the COE in preparation of MEOW's and innundation maps for LIS to ensure the highest accuracy and greatest applicability.

Recommendations # 4g: The SLOSH MEOW's and associated innundation maps should be evaluated to determine if they can also be applied (directly or modified) for use during extratropical storms.

APPENDICES

APPENDIX A: ASERT SPECIFICATIONS

The statewide automated flood warning system is called ASERT (Automated State Evaluation in Real Time). The initial phase of the ASERT system is now being installed and should be operational in late 1986. The system consists of 20 automated rain gages, 6 weather stations (including precipitation gages), 6 radio signal repeaters, and 2 base stations. Each base station includes an antenna, radio signal receiver, data decoder, microcomputer, ALERT software, and an uninterruptable power supply backup.

An automated coastal monitoring network that is compatible with the ASERT system will need to be compatible with and make use of the radio signal repeaters and base station components of the ASERT system.

The specifications provided on the following pages are taken from two sources:

1. Specifications for remote station transmitters and radio signal repeaters are taken from the bid specifications prepared by the Connecticut Department of Environmental Protection and the Federal Soil Conservation Service in 1984. Some modifications to these specifications have been made and other modifications may be made before the system is completely operational. Because some changes may still occur, no attempt was made to update the bid specifications to include any changes that have been made.

2. Specifications for the base station components are taken from product literature of Sierra Misco, Inc. which supplied all major base station components except for the microcomputer.

MATERIAL SPECIFICATION

624. TRANSMITTER

1. SCOPE

This specification covers the quality of the transmitter for the automated gages. The transmitter shall transmit data in a format readable by a Sierra-Misco Model 5051 receiver-decoder.

2. TRANSMITTER

a) Sensor input signals are analog 0-5V DC signal using digital SPDT switch contacts.

b) Signal transmitted in binary format consistent with NWS decoding software.

c) Transmission time of 230 milliseconds.

d) Sends 4 digit station ID.

e) Has 2 digit or greater accumulator (00 to 99) which is automatically resettable and counts up and down.

f) Input channels of 4 digits and 16 analogs.

g) Rechargeable gel cell battery to provide adequate power for one years' operation. If recharging is needed during the year, a solar panel or AC power, where available, will be used.

h) Frequency stability of 0.0005%.

i) Operates in a temperature range of -30°C to 60°C.

j) Audio distortion of less than 8%.

k) The transmitter shall have sufficient output to pass the acceptance test.

l) Generates 2 test signals every 24 hours.

3. FREQUENCIES

Repeaters & Gages	Receiving	Transmitting
Mohawk Mountain	171.875	169.425
Thomaston		171.875
New Milford		171.875
Barkhamsted		171.875
Norfolk		171.875
Sharon		171.875
Oxford	169.525	171.125
New Haven		169.525
Stratford		169.525
Oxford		169.525
Bethel		169.525
Southington Mt.	171.125	169.425
Plainville		171.125
Wallingford		171.125
Southington (Prec) - Sewer Plant		171.125
Southington (River)		171.125
Southington (Precip) - New Britian Reservoir		171.125
John-Tom Mountain	171.850	169.425
Mansfield		171.850
Ellington		171.850
Ekonk Mountain	169.475	171.850
North Stonington		169.475
Plainfield		169.475
Thompson		169.475
Plain Hill (Norwich)	171.125	169.475
Salem		171.125
Lebanon (Bartlett Brook)		171.125
Norwich (Precip)		171.125
Norwich (River)		171.125
Lebanon (Susquetonscut-Brook)		171.125
Lebanon (Deep River)		171.125
Mount Parnassus	169.525	171.850
Old Saybrook		169.525
Haddam		169.525
Direct to base stations		
John-Tom Precip		169.425

4. GENERAL

a) Moisture protected electronics located below ground.

b) Transmission at 300 baud consisting of four ten-bit words, including start and stop bits. Transmission interval of less than one-quarter second. This shall include transmitter warm-up period suitable for operation through a minimum of two radio relays.

c) Data transmission shall utilize binary format consistent with NWS decoding software - see attachment.

d) An integral programmable clock which triggers regular check signals for verification of system operation.

e) An automatic regulator which prevents a transmitter from remaining on.

f) Modular components capable of field swapping.

g) A selectable station ID on the electronic package.

h) Integration of the electronics and power supply into a single portable package weighing not more than 15 pounds, which is water resistant and will float in the base of the gage if it becomes flooded.

i) A carrying handle on the electronics package designed to allow fastening of the lifting rope without blocking hand entry.

j) All transmitters shall comply with FCC type acceptance criteria.

MATERIAL SPECIFICATION

622. REPEATERS

1. SCOPE

This specification covers the quality of the self-contained automated repeater.

2. VHF RECEIVER

a) A DC rechargeable, gel cell battery to provide adequate power for one year's operation. If recharging is needed during the year, AC power will be available for trickle charging.

b) Sensitivity of 12dB SINAD 0.35 microvolts and 20 dB quieting 0.50 microvolts.

c) Frequency stability of 0.0005% from -30°C to 60°C.

d) Modulation acceptance of 7KHz.

e) 3.0 dB gain VHF omnidirectional receiving antenna.

f) Antenna input impedance of 50 ohms.

3. VHF TRANSMITTER

a) A DC rechargeable gel cell battery to provide adequate power for one year's operation. If recharging is needed during the year, AC power will be available for trickle charging.

b) Frequency stability of ±0.0005% from -30°C to 60°C.

c) 7 dB Directional antenna except at Plain Hill which shall be a 3 db Omni directional antenna.

d) Power output shall be at least 25 watts.

4. GENERAL

a) All connections and low loss coax cables, as well as side mount hardware where needed, necessary to receive and transmit the required signal. All mounting hardware shall be stainless steel.

b) Time to receive and retransmit signal shall be less than 20 milliseconds.

625. RADIO FREQUENCY FILTER

1. SCOPE

This specification covers the quality of the radio frequency filter at the repeater sites.

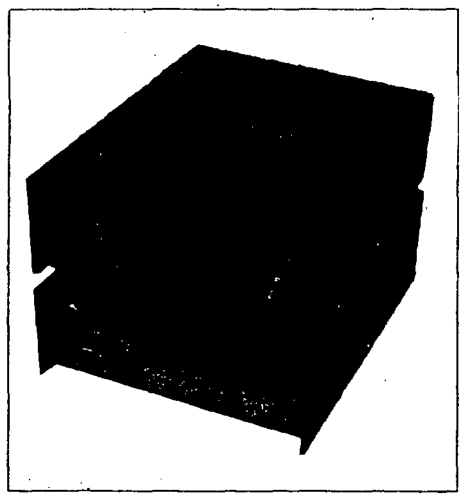
2. FILTER

A Decibel Products DB4002-2B (or equivalent) bandpass filter with an overall insertion loss of 1 dB or less to the transmitter R.F. output.

ANTENNA

DB224 VHF-OMNI 6 DB 360 Degrees Bracket for 2½" top mounting, side mounting available
Size: Length Approx. 20 Ft., Width 1½ Ft.

Model 5051R/D RECEIVER/DECODER



GENERAL DESCRIPTION

The Model 5051R/D Receiver Decoder receives transmitted data from field transmitters or repeater stations, decodes the data and provides an RS232C output for computer input. The receiver and decoder are separated into two units so that the receiver can be located near the antenna tower and the decoder can be located in the central office near the computer. This reduces the amount of coaxial cable needed, minimizing the signal lost, and increases the strength of the received signal. The receiver/decoder is supplied with 15 feet of interconnecting cable.

The receiver is operated by 12Vdc battery or 110Vac. A trickle charger is included for a 12V battery. To eliminate the loss of data during power outages, Sierra-Misco recommends the use of a battery for stand by power. The decoder may also be battery operated however, when a UPS is included for the computer it is normally operated by 110Vac and is backed up by the computer's UPS.

The base station receiver should be used with a high gain omni receive antenna. This will increase the incoming signal strength for remote sites which have marginal radio paths.

RECEIVER FEATURES

- Low power consumption
- Entirely automatic during operation, requires no manual supervision
- No external controls are available for people to touch and get the system out of adjustment

DECODER FEATURES

- The decoder has tone filters to eliminate noise and interference from possible adjacent voice channels. This assures accurate inputs to the computer
- Two RS232C output ports standard
- 12Vdc battery operated or 110Vac operated

SPECIFICATIONS

Receiver:
VHF Frequency Range: 135-174 Mhz
UHF Frequency Range: 400-512 Mhz
Sensitivity: 0.25 Microvolts Min. (12 dB Sinad)
0.35 Microvolts Min. (20 dB Quieting)
Frequency Stability: ±.001% (-30 to 60° C)
Channels: 1
Modulation Acceptance: ±5.0 KHz Nominal
Power Required: 12VDC, 50ma unsquelched
25ma squelched
Temperature Range: -40 to 60 degrees C
Duty Cycle: Continuous
Weight: Encased Unit: 3 pounds
Size: Encased Unit: 7¼" W x 2¾" H x 9" D
Antenna Input Impedance: 50 ohms

50501D Decoder:
Power Required: 110Vac/60Hz or 12Vdc
Current Drain: 50 milliamps
Operating Temperature Range: -30 to 60° C
Output: 2 channels RS232C with standard RS232C connector
Weight: 3 lbs.

Model 5073
HYDRALERT SOFTWARE

Software: Available ALERT software comes in two packages: standard and ENHANCED. Both versions have an automated flood forecast option. Each package is compatible with the U.S. National Weather Service ALERT standards and protocols.

- data displays
  - precipitation group summary
  - single station display
- remote user communications (e.g., telephone)
- National Weather Service text file transfer
- precipitation map
  - automatic hourly map
  - map up to 24 hours on-demand
- audio/visual alarm
  - precipitation
  - water level
- limited line printer output

STANDARD HYDRALERT SOFTWARE FEATURES

- automatic data recovery, formatting, and filing
- automatic error checking
- 100 sensor storage capacity
- 500 data reports stored per sensor
- data storage to nearest 1 minute
- environmental data types
  - precipitation
  - water levels
  - temperature
  - wind speed
  - wind direction
  - barometric pressure
  - relative humidity
  - snow pack water equivalent
  - analog sensor

Model 5073E
ENHANCED ALERT SOFTWARE

Enhanced ALERT software contains all the features available in the standard package *plus:*

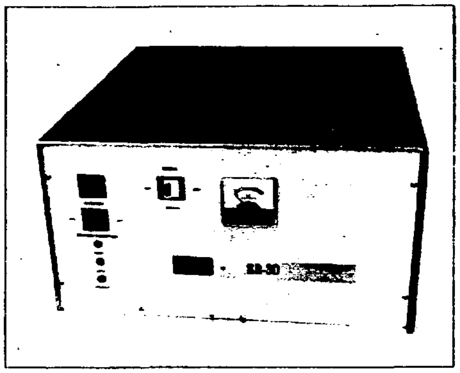
FEATURES

- full multi-user and multi-tasking capability
- menu-driven operation
- on-line user assistance
- dynamic data storage allocation
- data base utilities and editing
- data stored to nearest second
- manual data entry
- event reporting and interrogation capability
- data archiving and retrieval
- environmental data types
  - user specified
- data displays
  - multiple sensor type groups
  - precipitation group summaries
    - user selectable date and time interval
    - user selectable grouping
  - single station
    - user selectable date and time interval
  - data plots
    - user selectable date and time interval
- rating curves
- precipitation maps
  - up to 10 different map outlines
  - user selectable time and date interval
- text labeling of station names
- action/response displays
- external control capability
  - terminals map displays, optional
  - alarms beeper systems, optional
- audio/visual alarm
  - all data types can be alarmed
- complete line-printer output

International Hydrological Services
Enhanced ALERT System

UTILITY PROGRAMS

ALARM-GROUP	SET ALARM FOR A GROUP
ALARM-OFF	TURN OFF ACTIVE ALARMS
ALARM-SEE	LOOK AT ACTIVE ALARMS
ALERT	START ENHANCED ALERT
STREAM-SET	BASE SET STREAM GAGES
DEF-DBASE	DEFINE DATA BASE
DEF-MAP	DEFINE PRECIPITATION MAP
DEFGROUP	DEFINE PRECIPITATION GROUPS
DEFINE-RATING	DEFINE RATING CURVES
RAW-DATA	SINGLE STATION DISPLAY
PRECIP	PRECIPITATION GROUP DISPLAY
HYDROGRAPH	HYDROGRAPH PLOT
MAP-ALPHA	DRAW MAP BACKGROUNDS
NAMECHNG	CHANGE STATION NAME
PMAP	DISPLAY PRECIPITATION MAP
SENSOUT	DISPLAY SENSOR NAMES
SET-ALARM	SET SENSOR ALARMS
SHUTDOWN	SHUTDOWN ALERT
STAGES	SENSOR GROUP DISPLAY
STGGROUP	DEFINE SENSOR GROUPS
TIMEZONE	DEFINE LOCAL TIME ZONE



Model 5071UPS
UNINTERRUPTIBLE POWER SUPPLY

GENERAL DESCRIPTION

The 5071UPS is used to keep the computer operational during power failures and to protect the computer from low voltage "brown outs," lightning or other types of transient voltages and AC line noise.

Since even a 16 millisecond loss of power can cause the computer to drop out of operation and need rebooting, Sierra-Misco considers the UPS essential for the trouble free operation of the central station.

Operation is simple. AC power is converted to DC power and is used to trickle charge low maintenance 12 volt batteries. The batteries in turn supply power to an inverter circuit which creates AC voltage for the computer and decoder. There is no loss in synchronization, no loss in phase, and no loss in output voltage during an outage or return to AC power.

The 5071UPS incorporates a two-stage precision battery charge system that recharges the battery system within 6 to 8 hours after use. Once the batteries have reached 95% full charge, the two stage charge system switches to float operation.

When used with one 5071UPS-B Battery the UPS will operate a 5071 Central Site Display continuously for approximately 20 minutes. More batteries can be installed to allow for longer power failures. If extended power failures are anticipated a motor generator set should be used in addition to the UPS.

A battery cable and battery are supplied with the UPS.

SPECIFICATIONS

	Model 5071UPS (60 Hz) 5071UPS-1 (50 Hz)	Model 5071UPS-2 (60 Hz) 5071UPS-3 (50 Hz)
Power Out	300	600
Power In	110/220	110/220
Operating Time with 1 Battery	20 minutes	20 minutes
Operating Life of Battery	Approx. 5 years	Approx. 5 years
Noise Attenuation	>90 db	>90 db
Regulation	95 to 130 VRMS	95 to 130 VRMS
Size	22" x 17" x 10"	22" x 17" x 10"
Weight	80 lbs.	150 lbs.

MICROCOMPUTER

The base station microcomputer is an IBM PC/XT configured with 512 K of memory, one 360 K 5 1/4" floopy disk drive, and a 10 MB hard disk drive.

OPERATING SYSTEM

The Enhanced ALERT software works under the QNX multi-user, multi-tasking operating system.

APPENDIX B: STORM SURGE AND WAVE MODELS

B.1 STORM SURGE MODELS

B.1.1 Introduction

Theoretical models of storm surges all involve some degree of approximation and often questionable assumptions of the actual physics involved. The first theoretical models of storm surge were analytical, calculating storm surge along straight continental shelves with parallel contours and constant wind stress. To solve these equations, bottom stress terms had to be linearized, and other aspects of the physics were only approximate. In general, these analytical techniques provide a useful basis for understanding some of the physics of storm surges, but lack the full physics governing the process required for accurate predictions.

An alternative approach to storm surge modeling arose once computer time became more readily available, and numerical techniques acquired more widespread popularity. In the past fifteen years, ever-increasing numbers of numerical models have been developed which can address storm surge problems. Many of these models are similar, differing only in representation of some of the terms in the equations of motion, or in the precise detail of the numerical implementation of a term (a good example being the variety of ways to implement the nonlinear inertial terms). Many of these models differ in a more fundamental fashion, however, in that they represent different physics.

As an example, bottom stress -- the resistence of the rough ocean bottom to propagation of any surface disturbance -- can be approximated in many ways. One approximation invokes a higher order turbulence closure scheme to approximate the effects of bottom friction. This yields adequate results in many cases, but also increases computational time and requires more assigned parameters. A simpler approach is to incorporate a linear bottom friction model, where the friction coefficient is dimensional because of the linearity in velocity.

More complex, but largely empirical in derivation, is a quadratic friction term, where the friction coefficient describing the coupling between the flow and the bottom is a more appealing nondimensional number. These techniques generally ignore flows at different time scales. For instance, a storm surge model will ignore flows at much higher or lower frequencies. Although tides may be incorporated in these models, the effects of surface gravity waves (wind waves) and other disturbances generally are not included. Recent theory has shown that higher frequency flows increase the bottom friction associated with longer period motions such as tides and storm surges, so future storm surge models will have to improve the physics of this term.

The above example illustrates the magnitude of the uncertainty in developing and applying a storm surge model. Computer methods have increased our abilities to consider more realistic physical cases, but there are still theoretical uncertainties as to what constitutes a realistic physical case. The importance of differences in model details are vigorously debated among scientists and engineers developing these models. The bottom line is that there is no single model which will best fulfill the job of accurately predicting storm surge. A model which performs well at one site may not perform well at another, because of improper physics. For instance, a model with a poor bottom friction representation may perform well in a deeper embayment, but do a much poorer job in Long Island Sound, which is much shallower. The best model for a particular area may also be too expensive to run for the variety of cases required for compilation of an atlas of storm surge scenarios, for instance.

Following is a brief overview and description of the two major techniques for estimating storm surges, and how they have been and may be applied to the Connecticut coast.

B.1.2 Statistical Storm Surge Studies

Many of the estimates of storm surge height are derived from historical data concerning past storm surges. To interpret these past results and to apply them to forecast future anticipated storm surges, the observations must be placed into some statistical framework. This statistical framework is fraught with uncertainties and assumptions, but can be applied in a climatological sense to provide estimates of expected surges. This method, however, cannot provide estimates of expected surge during a particular storm, a shortcoming making them of limited utility for this study.

Where possible, tide gage data are used to generate statistics of storm surges (46, 187) in concert with non-gaged estimates of surge level during large hurricanes and storms. These observations are then fit to a statistical distribution of storm surges and superelevation. Boon et al. (187) use a Poisson distribution, others use a Weibel distribution, while Dewberry and Davis (46) use a Pearson Type III distribution. There is considerable debate about the proper type of distribution to use; if the forecast is for a 100-year frequency or greater, the results may not be too sensitive to the distribution. However, 500-year events are particularly susceptible to differences in distribution selected.

Another common problem in using statistics of extreme events to forecast flood levels is the occurrence of outliers. Outliers are generally extreme events which significantly degrade the fit of the data to a statistical distribution, compared to all other data. These outliers commonly are larger events, which should influence the forecast. There is no standard technique for treating outliers, but it is not uncommon to leave these out if the other data fit the statistical model without it. Although not uncommon in practice, it might be better to suggest a different model than to eliminate data because of lack of fit.

Most statistical storm surge models neglect changes in relative sea levels. Since relative sea levels are indeed increasing along the Connecticut coast, this should be considered in longer-term estimates of storm surge. It will have no significant effect on storm surge estimates for time periods shorter than 20 years or so.

STATISTICAL STORM SURGE STUDIES FOR LIS

There have been three major studies of statistics of storm surges along the Long Island coast of Connecticut. The first, in 1973, was published by the New England Division of the U.S. Army Corps of Engineers (COE) (89). Those study results were revised in 1980 during the second study by the COE (6) using tide-gage data from five stations (Willets Pont, NY; Stamford, Bridgeport, New London, and Stonington, Connecticut). A major decision in the 1980 study was to eliminate the 1938 hurricane from the statistical model, thereby lowering the 100-year flood estimates, particularly in eastern Connecticut. Tidal flood profiles from this study are shown in Figure B.1.

In 1982 Dewberry and Davis (D&D) performed the final study for the Federal Emergency Management Agency (FEMA) (46), which was essentially a review of the 1980 COE study. The major difference resulted in D&D's inclusion of the 1938 hurricane in their statistical model fit, particularly in eastern Connecticut where the 1938 surge was highest. D&D recommended the adoption of the COE 1980 surge profiles, except in the New London area where an increase was suggested to fit the 1938 hurricane data. The resulting profile (Figure B.2) was adopted by FEMA for updates to its coastal flood insurance studies.

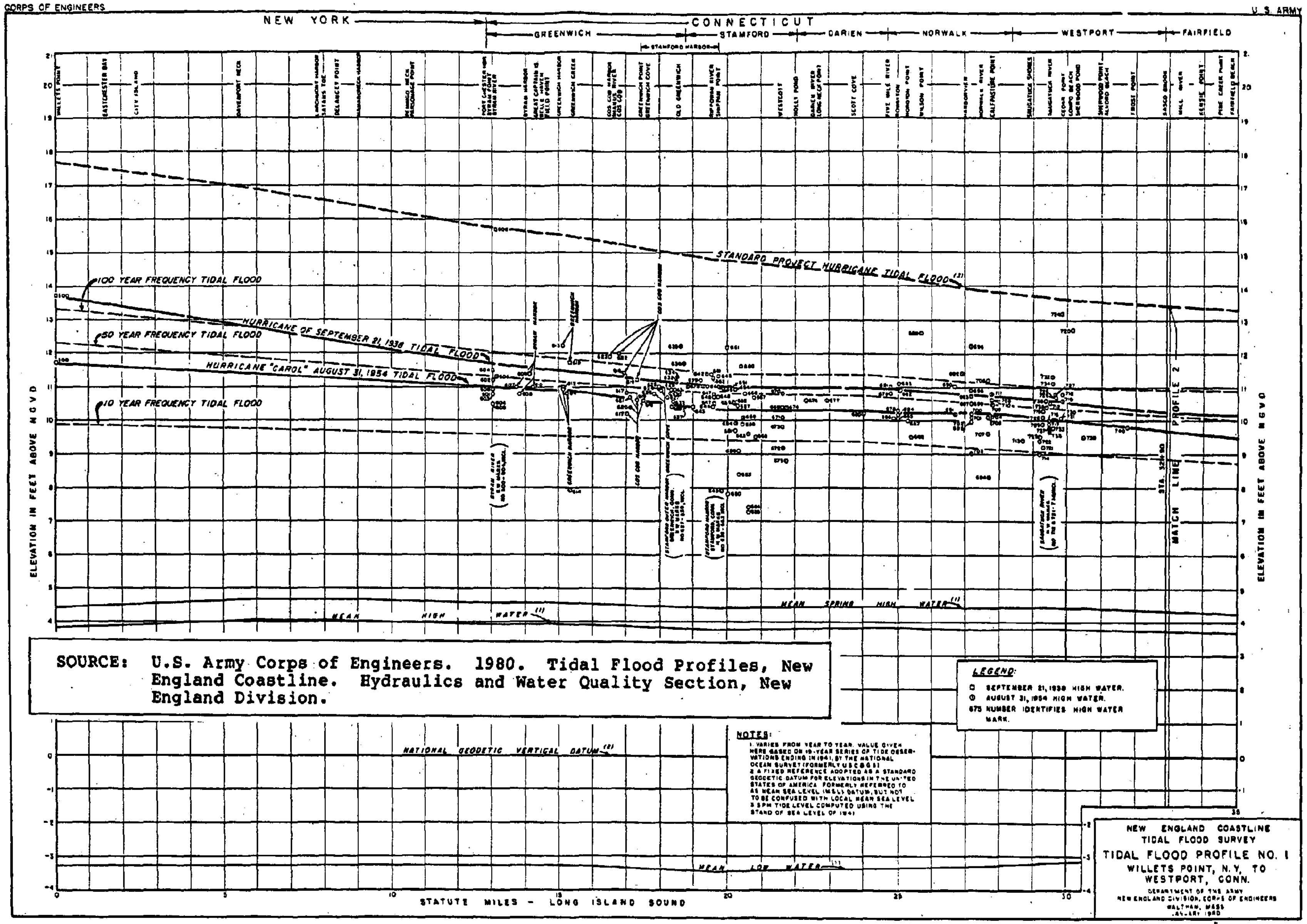
The latest 100-year flood profile shows the highest flood level in western Connecticut (12.2 feet NGVD), lowering to 10 feet by Stratford. From Stratford east the level rises to about 10.7 feet at East Haven, followed by a gradual decrease to about 10.0 feet at Waterford. At New London the level is 10.0 feet NGVD. To the east of New London the flood increases from about 10.0 feet to 10.8 feet at Stonington.

These flood profiles show that storm surge increases dramatically within the Thames River estuary. According to the COE 1980 study, storm surge increased from 9.5 feet to 14.3 feet NGVD at the 100-year level as the distance from the mouth of the Thames River increased. The 1938 hurricane surge ranged from 9.8 feet at New London up to 15.2 feet in Norwich. This estuarine effect may not be modeled adequately by the numerical approximations, so care should be taken to assure that this increase in height in embayments is known to flood management personnel.

NWS STORM SURGE MODEL FOR EXTRATROPICAL STORMS

The NWS has adopted a storm surge model for extra-tropical storms (73) which is a statistical storm surge model (or empirical, in NWS's terminology). Using simple regression methods, the observations of storm surge at ten coastal locations (with tide gages) are related to sea level pressure values as forecast by the National Meteorlogical Center (NMC). Using 68 storms occuring from 1956 through 1969, regression equations were established using a screening procedure, to allow the best fit between observed surge and sealevel pressure, at a minimum number of stations to reduce artificial predictability and increase forecast skill.

The procedure is entirely empirical, and is based on the observed and theorized relationship between atmospheric pressure and storm surge. The errors in this empirical technique can be very large, although it does a reasonable job forecasting during some storms. These regression equations apparently have not been updated since 1974, and there are no present plans to do so (71).



SOURCE: U.S. Army Corps of Engineers. 1980. Tidal Flood Profiles, New England Coastline. Hydraulics and Water Quality Section, New England Division.

FIGURE B.1: Tide Levels and Flood Profiles for Connecticut

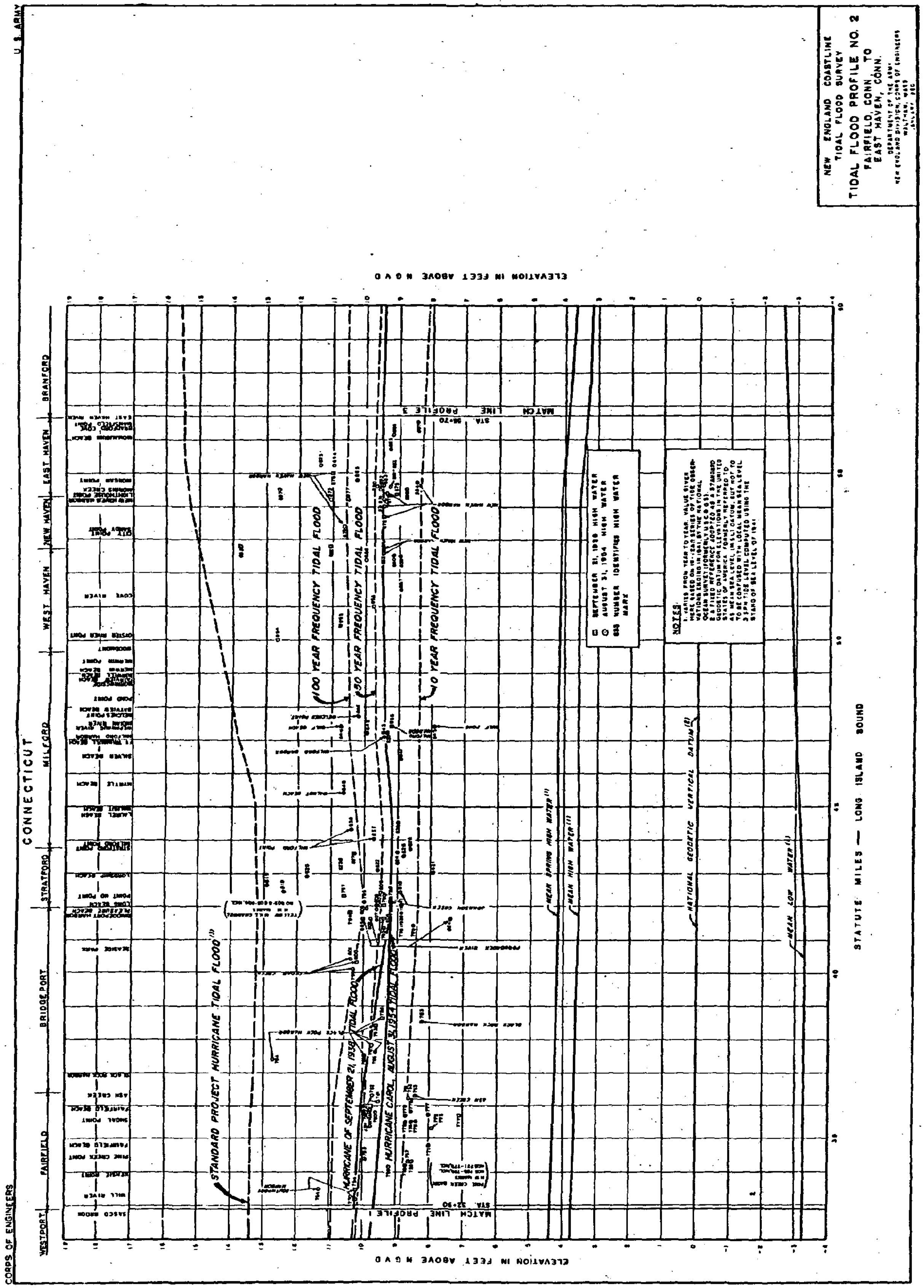


FIGURE B.1: Tide Levels and Flood Profiles for Connecticut (Cont'd)

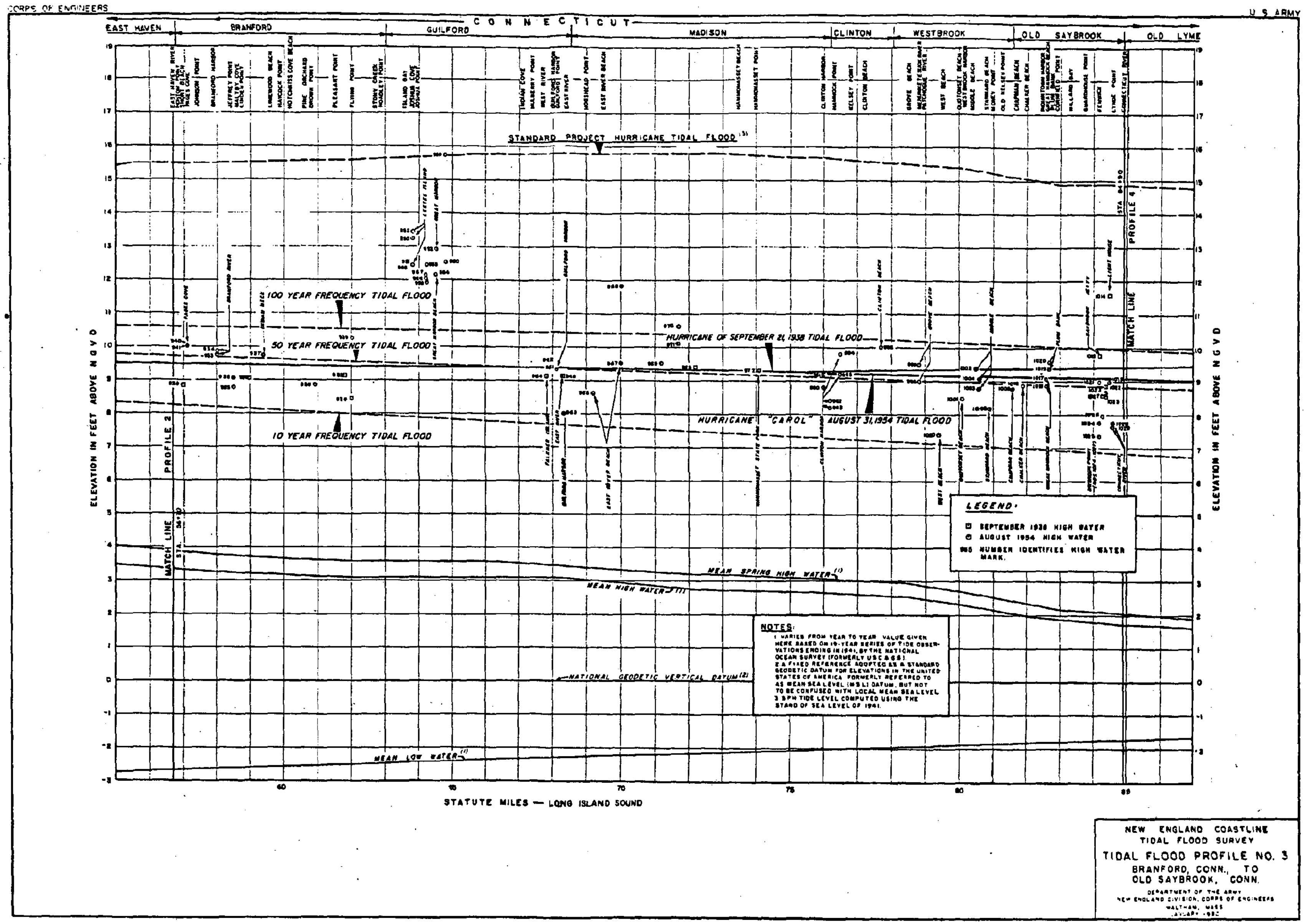


FIGURE B.1: Tide Levels and Flood Profiles for Connecticut (Cont'd)

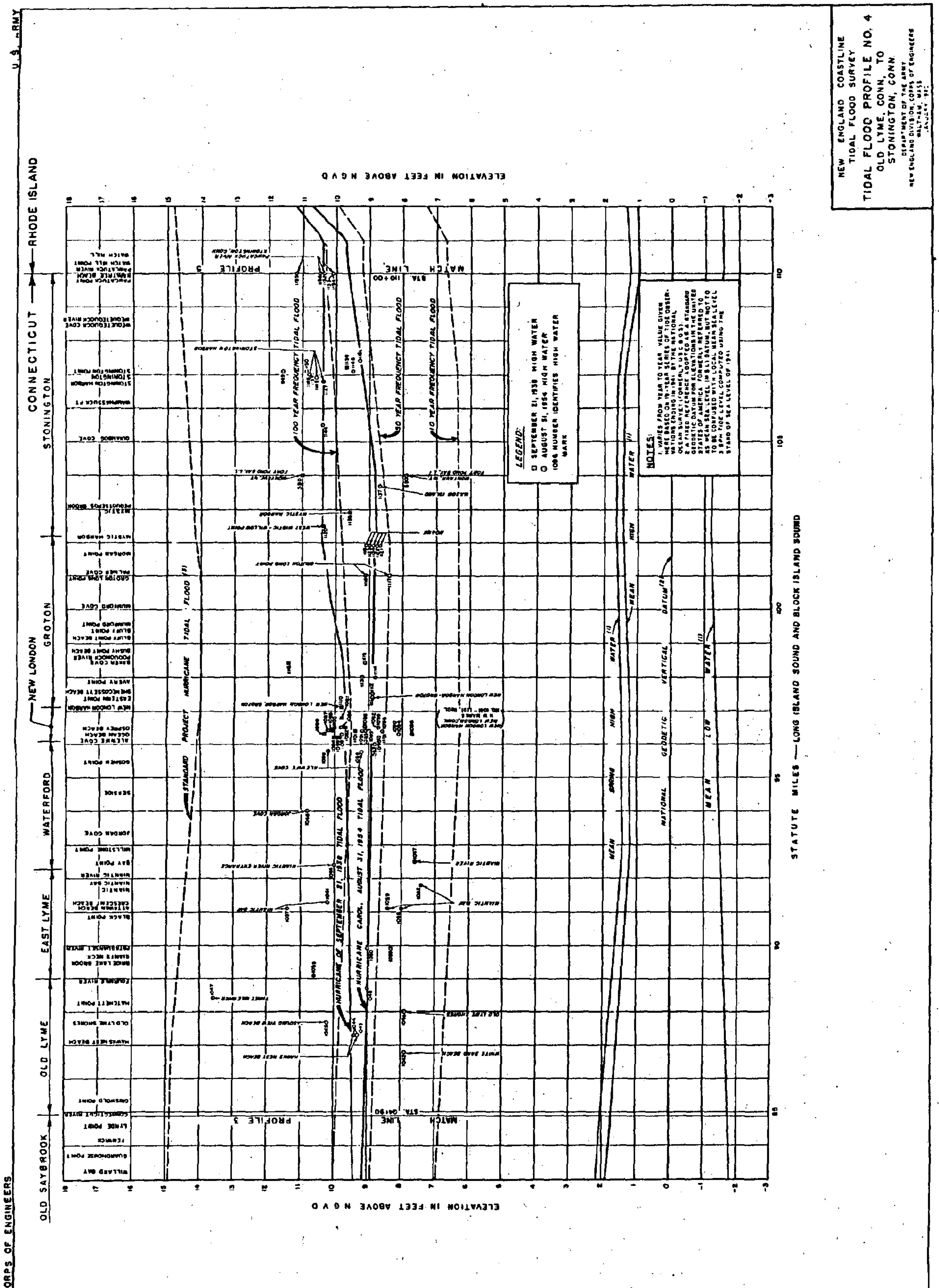


FIGURE B.1: Tide Levels and Flood Profiles for Connecticut (Cont'd)

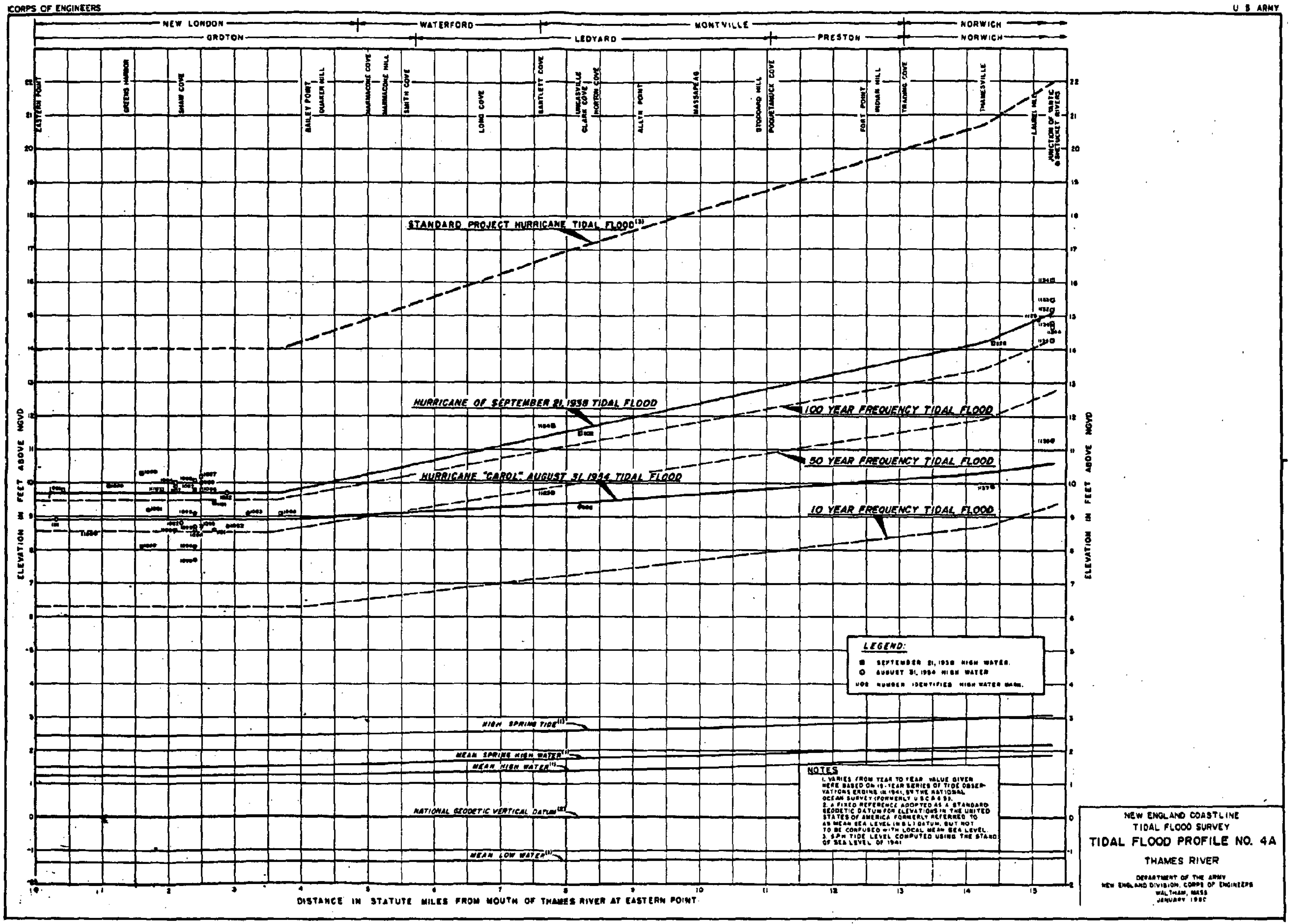
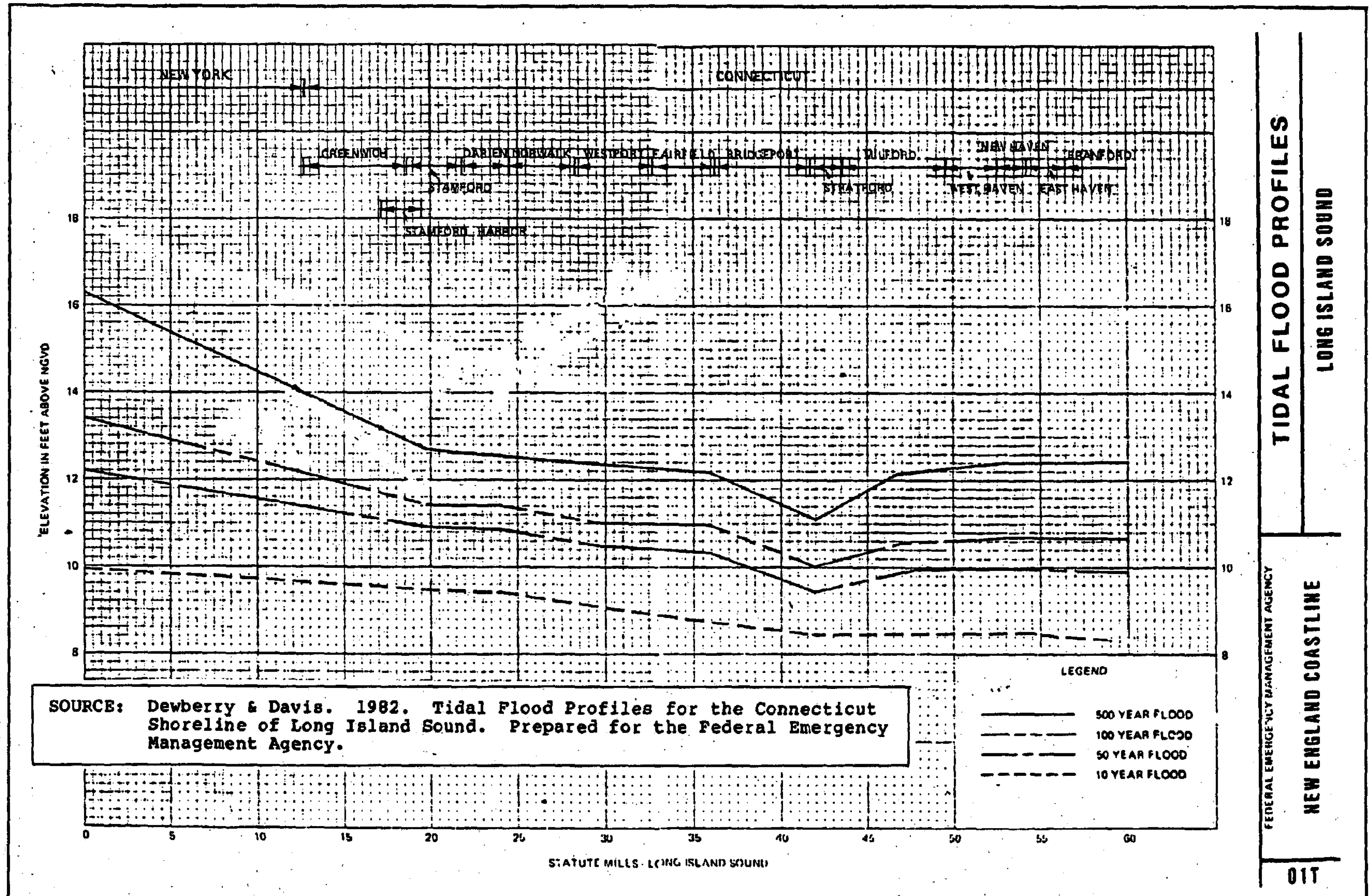


FIGURE B.1: Tide Levels and Flood Profiles for Connecticut (Cont'd)



SOURCE: Dewberry & Davis. 1982. Tidal Flood Profiles for the Connecticut Shoreline of Long Island Sound. Prepared for the Federal Emergency Management Agency.

FIGURE B.2: Flood Profiles for Connecticut

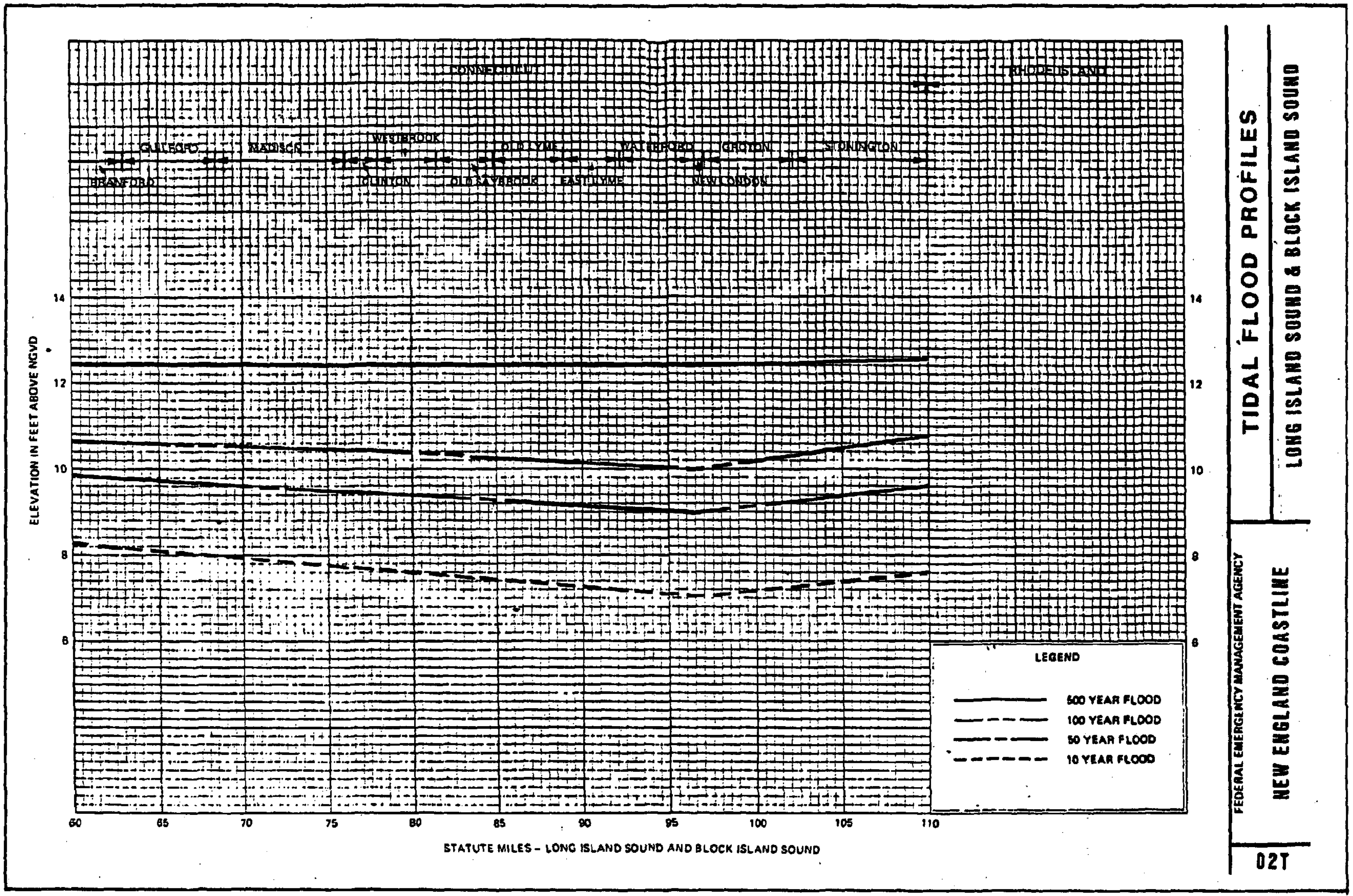


FIGURE B.2: Flood Profiles for Connecticut (Cont'd)

For most of the ten stations, two regression equations were developed. One, utilizing sea level pressure at several locations, is used on the NMC computers to generate a storm surge forecast that is provided to local National Weather Service offices. A second equation, utilizing sea level pressure from fewer locations, can be solved manually by local weather service offices to forecast storm surge.

Stamford, Connecticut is one of the ten locations for which regression equations were developed. Only five sea level pressure stations are used in the Stamford equation (as opposed to 7 - 15 stations for most locations), and the same equation is used by both NMC and local weather service offices. The equation used for Stamford is shown at Figure B.3.

$$SS(SFD) = 24.06 + .06265\ P(12)_t - .07930\ P(31)_t - .03170\ P(40)_t + .05521\ P(18)Zt - .02926\ P(27)_t$$

SS = Storm Surge (in feet)
P = Sea Level Pressure (in millibars)
(12) = Grid Point for Sea Level Pressure
t = Time of Sea Level Pressure Observation

FIGURE B.3: Regression Equation for Extratropical Storm Surge Forecast, Stamford, Connecticut

Figure 4.1 illustrates the forecast vs. observed storm surge at Stamford for two storms in 1972, and indicates that the model consistently over-estimates storm surge at Stamford. The COE, which uses NWS storm surge forecasts as an aid in operating the Stamford Hurricane Barrier, also reported that forecast surges are usually higher than recorded surges (25,39).

If the State of Connecticut were to incorporate this type of extratropical storm surge forecast into a coastal flood warning system, several improvements to the current procedure are suggested. First, the regression equations should be developed for additional locations having storm surge records (Bridgeport, New London, Old Saybrook). Second, the equations should include additional sea level pressure stations which should be carefully chosen based on there predective capability as indicated by historical records for many recent storms. This improvement in the methodology of regression is needed to assure robust estimates, and minimize problems of artificial predictability.

The utility of these statistical techniques is limited, however. It is recommended that this methodology be replaced by dynamic models of storm surge, even for extratropical storms.

B.1.3 Numerical Storm Surge Models

To predict the storm surge associated with a storm of arbitrary features (such as path, wind speed, size), the statistical storm surge summaries are inadequate. Necessary in this situation is a realistic model of the effects of winds on the surface of the water, including all physics appropriate for the ocean basin of concern. Generally the model uses as input some representation of the storm, including its path, wind distribution, and speed.

For the case of hurricanes, such models have long been in existence. The first such model, developed by Wilson in 1957 (188), includes the parameters of central pressure index, the distance from the hurricane center to the point of maximum winds, and the forward velocity of the hurricane. Subsequent representations of hurricanes include a more realistic description, increasing realism while also increasing computational time.

Models for extra-tropical storms are much more difficult to generalize, and are derived most often from synoptic weather charts, updated every four-to-six hours.

MODEL TYPES AND PARAMETERS

The number of numerical models which have been applied to storm surge problems is very large, increasing rapidly each year. More than 30 such models were reviewed as part of this study. The different types of models and some of the important parameters used in such models are reviewed briefly in the following pages. Although not exhaustive, this discussion provides some understanding of the difficulties in representing the physics of the ocean in a numerical format, and illustrates some of the pitfalls to be avoided.

For further review of the state-of-the-art in storm surge prediction, several references are available. Marine Forecasting by Nihoul (189) provides a useful review of the concepts of storm surge modeling, current to the date of publication. Pagenkopf and Pearce (190) provide a detailed discussion of several types of storm surge models, their differences, and their performance in predicting surges during a hurricane. Many similar publications exist, from an introductory level up to the most current.

Numerical storm surge models use the basic hydrodynamic equations governing fluid flow as a starting point. The appropriate equations are the Navier-Stokes equations for fluid momentum, and the continuity equation. The differences are in the way these equations are implemented numerically, which terms are included, how the terms are included, and the application of the solution of these terms to a physical problem.

Some of the important classes of solution are discussed here. Basically, the storm surge models include inertial effects, incorporating the unsteady term in the equations of motion; the convective term; and a Coriolis acceleration. The other terms in the equations are the pressure gradient term and the dissipation term. Besides differences in numerical implementation and gridding of the equations, the parameterization of the dissipation term is one of the largest differences between various models.

One of the most fundamental differences between models is the numerical scheme implemented. Two methods for approximating the equations of motion numerically are finite difference and finite element techniques. Finite element techniques have only recently (since early 1970's) become popular in ocean hydrodynamics, while finite difference techniques have been around a long time. Pakenkopf and Pearce (190) provide a quantitative comparison between these two techniques, using a modified finite difference model of Pearce (191) and finite element model of Connor and Wang (192) and Wang and Connor (193). The finite element model is generally considered to be more appealing because of its flexible grid, where grid elements need not be of constant size. The finite element implementation is normally considered to be more expensive to run (194) although this is disputed by (190,195). Finite elements also have different stability constraints than finite difference, allowing larger time steps for a given level of numerical stability.

Finite difference techniques are still the most widely used in spite of the advantages of the finite element models. The higher cost of the finite element technique has made many investigators shy away from it. Although for a long-time-simulation the finite element scheme may be cheaper, it is normally much more expensive for shorter simulations. The finite difference method is also the most widely taught in engineering schools.

To get around the problem of rectangular grids required by finite difference models, several interesting schemes have been proposed and implemented. First, a boundary-fitted coordinate system has been suggested such that in a transformed coordinate system the grid is rectangular, but in the non-transformed coordinate system the grid is not regular. This allows the models to be adapted for specific geometries of shorelines. Examples of this technique are Johnson (196), Thomson et al. (197), and Spaulding (101).

Another solution has been to develop a methodology for irregular grids in finite difference techniques. An important series of articles on this technique have been produced by Thacker (197, 198, 199). In this methodology, an irregular grid is produced to conform to the boundaries of the problem, and the appropriate numerical transformations applied to it. Although this technique has provided some interesting results, there is still a question about stability of the method (195), and arguments about why it may be more appropriate than alternative techniques. Finally, a variety of other grids have been applied, such as curvilinear grids and stretched rectangular grids. These all must be applied with care, to avoid or minimize stability problems, and are generally difficult to achieve maximum resolution in those areas where it is needed most.

Since computational time and resultant expense increases as the size of the computational grid element decreases, there is considerable work on reducing the size of the grid to an acceptable level, and living with the degree of accuracy resulting (finite element grids do not have this limitation). The smaller the grid size the smaller the time step required to achieve stability; hence the trend (discussed above) towards achieving finite difference grids having variable resolution. One way of getting around the limitations of the finite difference restrictions is to run two grids, in a nested sense. A coarse grid is run to cover the offshore conditions, where the fine resolution is not needed, while a finer mesh grid is run inshore, where resolution is essential. This is an acceptable compromise for modeling areas with variable resolution requirements using finite difference techniques. It has been used in Long Island Sound, for instance, by Gordon and Spaulding (99) and Spaulding and Gordon (100) to calculate the tides.

Besides the numerical implementation of the equations of motion, and the problem of gridding the geographic area to obtain adequate resolution at a reasonable cost, there is a consideration of the dimensions of the equations to be calculated. The simplest models are one-dimensional, which the analytic solutions tended towards. The next step is two-dimensional, the most common being a vertically-integrated model with the vertical dynamics ignored. The two horizontal coordinates, x- and y-, then express the momentum balances in the flow. Finally, there is a class of three-dimensional models, which are required to specify flows when the vertical dynamics are important. Generally as the number of dimensions increases, the cost of the analysis increases. Many examples of these different models exist, and are not detailed here. Most storm surge models are vertically-averaged two dimensional models, since the vertical dynamics are not particularly important in describing storm surge processes. Although this is an assumption placing a constraint on the accuracy of the model, it is not an unreasonable assumption.

Other differences between models include the parameterization of bottom friction and other dissipation processes. Many models use a quadratic bottom friction, where the dissipation is proportional to the square of the near-bed velocity. Commonly, a Chezy-type friction is applied, or a Manning formulation. These ignore the effects of the bed geometry and the surface wind waves on the bottom friction, a step which is reasonable in deep water but not acceptable in shallow water. As Grant and Madsen (200, 201) have shown, in shallow water where waves are important, these higher frequency motions increase the drag felt by any longer period motions across the bottom. Incorporation of the effects of the non-linear interaction between waves and currents is required if dynamics of shallow water flows are to be described accurately. Few numerical models incorporate this bottom friction due to wave-current interaction, but for Long Island Sound such a physical model should be included for accurate storm surge prediction.

Another matter of critical concern in numerical modeling is the prescription of boundary conditions. Boundary conditions have a direct impact on the storm surge calculations, and must be analyzed critically. For instance, at the coastal boundary, several types of boundary conditions are possible. First, there can be zero velocity normal to the boundary, a condition which is reasonable if the coastline is a high, steep cliff. This is a common boundary condition. However, in the case of a low-lying shoreline, where wetting will occur, this is an inappropriate boundary condition. In this case, more realistic boundary conditions must be applied, with a knowledge of how flooding occurs. This entails the use of a boundary condition applied along a moving boundary, a modeling problem which has been solved before. This moving boundary requires fine resolution, again requiring a nested grid to allow computations to proceed at a reasonable cost.

On the open boundary which terminates the model to seaward and laterally, a similar dilemma arises. An open boundary will have several possible conditions applied to it. Physically, one requires a description of the physics outside of the region, to match with the physics derived for the interior with the model. This is not generally known. To minimize these open boundary problems, one generally applies open boundary conditions far from the coastal region of interest, and applies a condition which is not unreasonable physically. The sensitivity of the surge calculation to different open boundary conditions can be determined numerically; if the model is extremely sensitive over the time duration of the simulation, a more complicated open boundary condition may be applied.

The simplest open boundary condition is that there is a continuity in sea surface across the boundary, and that there is no flux parallel to the boundary. As emphasized by Reid (202), this condition corresponds to complete reflection of gravity waves. If this reflection is not large, or the time interval sufficiently small, this may not be a restrictive case. When the surge behaves like a free wave, a radiation condition must be applied to minimize the effects of the reflectivity of the open boundaries (203).

CONSIDERATIONS FOR A LIS MODEL

This brief overview of the modeling problems associated with implementing the equations governing storm surge illustrates the variety of uncertainties and problems associated with these models. With the debate within the scientific and engineering community still showing no signs of abating, there is no clear consensus on which model to use for what situation. There are some clear trends, however.

1) A two-dimensional numerical model is appropriate for storm-surge calculations. If the 2-D model uses finite difference techniques, a nested grid must be used. If the 2-D model is finite element, then a single grid could be used.

2) The open boundary conditions must be implemented carefully. On the open boundaries, a radiation condition may be required for certain storm paths. Since there is only a single open boundary in the Long Island Sound case, this implementation should not be difficult. If a radiation condition is not used, numerical experiments must be run to show that the model is not excessively sensitive to the type of open boundary condition selected.

3) The shore boundary conditions should reflect the possibility of land wetting for the low-lying areas of the Connecticut and Long Island shores, paying particular attention to the estuaries of Connecticut. With the large storm surge in the Thames River, for instance, due consideration must be paid to their effect on storm surge downstream. Again, numerical simulations should be required to demonstrate the sensitivity of the model to the boundary conditions selected.

4) Any model will require input of meteorological conditions to run the model. Some models will work off atmospheric pressure input, others need calcuated winds. Some models require speed of movement of the storm, others will interpolate from synoptic weather charts. For tropical cyclones, most models incorporate a simple model of winds within a cyclone, requiring only parametric input such as central pressure anomaly, some length parameters relating to winds, and speed of propagation. Preferable by far is a model which accepts atmospheric pressure input, and calculates the surface wind stress field from that. A comprehensive storm model may not apply to all types of coastal storms, but should be emphasized in future research on progress

in storm surge modeling.

5) Shallow water processes should be represented well in any model of Long Island Sound. Bathymetry must be input with as much resolution as possible, and incorporation of nonlinear bottom stress due to wave/current interaction should be made if possible.

6) Because of the effects of tides on storm surge, the numerical model should combine a tidal model with a pure storm surge model. This way total water elevations can be predicted, not just the storm surge component. If this model is run in real-time, such a tidal inclusion is straight-forward, and is routinely performed. If the model is run in a forecast mode with an eye towards generating an "atlas" of storm surge scenarios, then the tide must be added in after the model is run.

NUMERICAL STORM SURGE MODELS USED IN LONG ISLAND SOUND

Several numerical storm surge models, or portions of larger models, which have been used in Long Island Sound are briefly reviewed below.

Laevastu and Callaway (204) had a 2-D finite difference model of Long Island Sound as part of a larger model. This model had a grid spacing of 6.6 km. The grid is so coarse as to be of little value in the prediction of local storm surges.

Leendertse and Liu (205) applied a 3-D numerical finite difference model to Long Island Sound, using a horizontal grid spacing of 1.9 km. These were of short duration (order of a single tidal cycle), the primary intent being to estimate turbulent energy fluxes in the region.

Beauchamp and Spaulding (206) developed a tidal model of Long Island Sound as part of the New England Bight, using a 2-D finite difference model with 1.852 km grid spacing. With limited observations available against which to compare the model, the work could not be evaluated completely.

Murphy (207) applied the same 2-D finite difference model to a small area within Long Island Sound. The results are not particularly applicable to the present study.

Two models will be discussed in a little more detail: one by Spaulding and Gordon (100), and the SLOSH hurricane model by NWS (93, 94)

Spaulding -- Spaulding and his associates have extensive experience in modeling the waters of southern New England. Papers by Gordon and Spaulding (99) and Spaulding and Gordon (100) discuss the application of a nested numerical tidal model to the southern New England waters, including Long Island Sound. Although primarily a tidal model, it can be adapted easily to include storm surge effects. The model is a 2-dimensional, vertically integrated finite difference implementation of the equations of motion. It has ignored the convective acceleration terms, and employs a Chezy-type bottom friction formulation. It ignores the wave-current interactions and their effect on bottom friction. The larger grid interval was 5.55 km, while the smaller grid interval was 1.852 km. The model appeared to work well on tidal time scales associated with this study.

Since storm surge effects were not included, there was no wind stress term, and the time history of development of a wind field could not be included. In a later paper (101), wind stress (or surface stress) was included in the formulation using boundary fitted coordinates, and applied to the North Sea. Any future application of the Spaulding-type models must include a storm model for generating vector wind fields. Such a model is not described in the literature in connection with the tide models cited above.

NWS SLOSH Model -- SLOSH (Sea, Lake, and Overland Surges from Hurricanes) is a numerical tropical storm surge model developed for real-time forecasting of hurricane storm surge along the continental shelves. It was adapted from an earlier model used by NWS, SPLASH (Special Program to List Amplitudes of Surges from Hurricanes). It is a two-dimensional, finite difference numerical model, with a curvilinear, polar coordinate grid (Figures B.4. and B.5) to increase near-field resolution, while sacrificing far-field resolution. The model includes a storm wind model, which is fed by several time-dependent meteorological storm variables:

1) Latitude and longitude of storm positions at 6-hour intervals for a 72-hour storm track. This begins 48 hours before the storm's nearest approach, and ends 24 hours after the nearest approach.

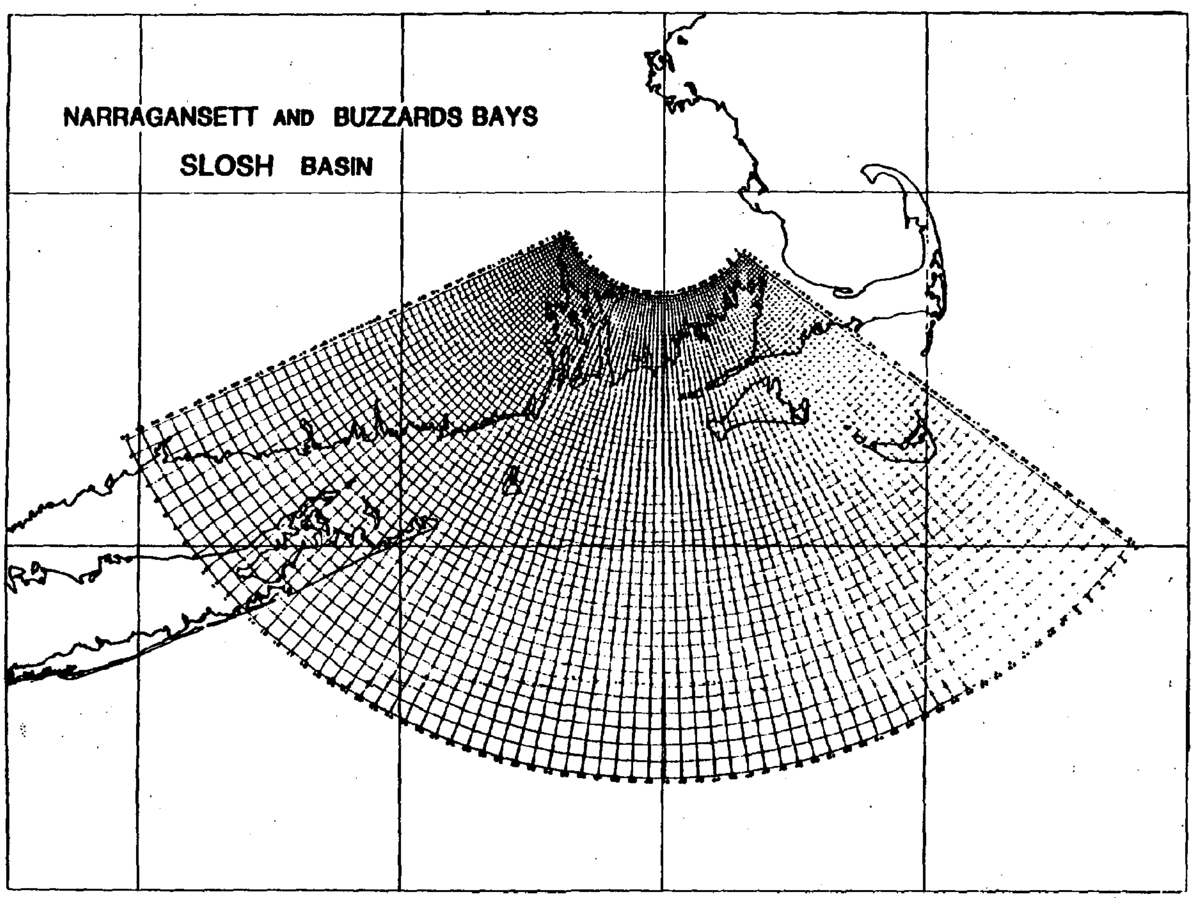
2) Storm central pressure at 6-hour intervals.

3) Storm size (center to region of maximum winds) at 6-hour intervals.

Wind stress vector fields are computed independently by the model, and are not input parameters. The initial height of the still-water surface before the storm is required. Far-field boundary conditions are computed far from the region of forecast interest to minimize their effects on the simulation. All geographical and bathymetric data must be input by the user, continually updating it in the case of real-time simulations to assure proper boundary performance.

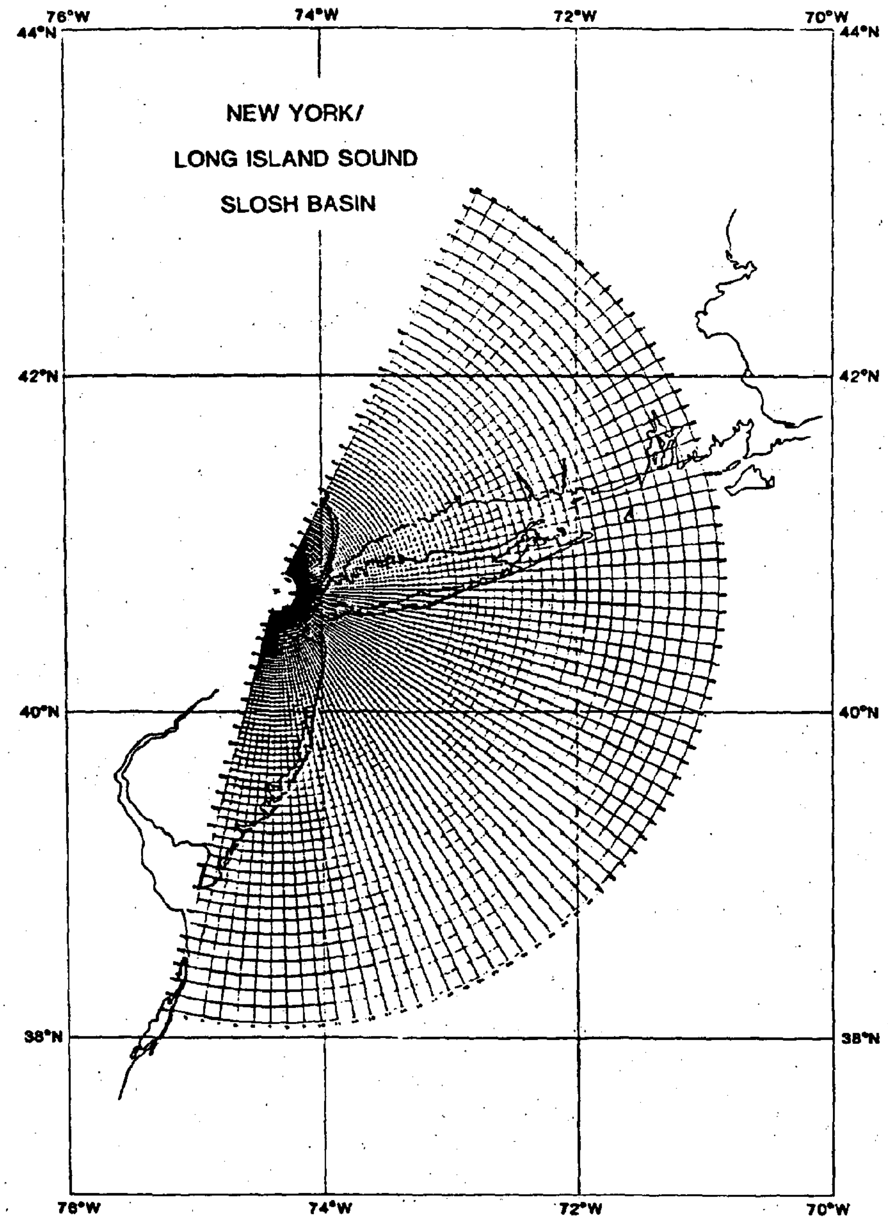
The SLOSH model makes several approximations. First, it does not include the advective terms from the equations of motion, since they have been shown to be small except in regions of large velocity gradients. Second, it incorporates a time-history bottom stress formulation (208), which does not incorporate Chezy-type friction coefficients, nor wave-current interactions. NWS acknowledges that the wave/current interactions are important on shallow shelves, but not on those of intermediate depth. Since Long Island Sound is a shallow shelf, bottom friction due to nonlinear wave/current interaction should be included. Other wind-wave effects such as run-up and set-up are not treated explicitly. They are treated implicitly in their use of bottom stress terms and other terms which are derived empirically from a historical data base. These wave terms act as noise sources, and their effects are included although not in a physical manner.

The SLOSH formulation does not include a tide model within it. The reason for this is the uncertainty in timing of tropical cyclones with respect to the surface tide. The second reason is that the SLOSH model is also used in a forecast, or "atlas" mode, where the storm surge is simply added to the corresponding tide. The error in not including the tidal calculation arises in the finite amplitude terms, where the surface tide may raise or lower the



Source: Techniques Development Laboratory, National Weather Service, Silver Spring, MD.

FIGURE B.4: Polar Coordinate for Narragansett and Buzzards Bays SLOSH Basin



Source: Techniques Development Laboratory, National Weather Service, Silver Spring, MD.

FIGURE B.5: Polar Coordinate for New York/Long Island Sound SLOSH Basin datum on which the storm surge acts. This should not be a major drawback in the Connecticut coastal area where tides are relatively low.

In application to the Connecticut coast, the SLOSH model has some problems inherent in it. Because of the shallow nature of Long Island Sound, the bottom friction formulation used in SLOSH will not correctly predict dissipation. Future improvements to SLOSH could include better representation of the physics of the bottom boundary layer, which could be done with no large increase in run costs.

If the SLOSH results do become available for the Connecticut coast as they should in the near future, careful comparison with observed storm surge should be carried out, and the source of any discrepancies identified. Bottom friction is one source which could be poorly represented by SLOSH, but locally advective effects could be important (they are ignored by SLOSH).

Another major concern in the Connecticut coast is the effect of Long Island on tropical cyclone passage. As seen in the 1976 Hurricane Bell and 1985 Hurricane Gloria, Long Island appears to have a major effect on the wind field of hurricanes. If the forecast winds were much larger than actual winds, hurricane surge would be overpredicted, with consequent increased expenses associated with evacuation. This emphasizes the need for evaluation of the model locally, where the wind field around a hurricane becomes extremely complex. The 1938 hurricane and the 1985 Gloria would be useful examples against which to compare the wind stress model and resulting storm surges.

The polar grid must be implemented carefully along Long Island Sound to assure a uniform grid. Large alongshore differences in grid spacing would result in greater uncertainties in storm surge simulation in some areas than others. The State should consult with NWS when model simulations are run.

B.2 WAVE FORECASTING/HINDCASTING MODELS

B.2.1 Introduction

Wave forecasting and hindcasting are accomplished by approximating the physics of wave generation and wave transformation by parametric or numerical methods. Although these techniques date back quite a few years, the earliest publication in book form of which is Sverdrup and Munk (209), recent advances in these techniques make them more reliable and accurate. Since these techniques are only approximate, they don't reproduce exactly the correct physics behind wave generation and transformation. Some of the techniques are more appropriate for deep water uses (such as the Navy's Fleet Numerical Weather Central wave model), while others do a much better job approximating physics of shallow water waves. Some require elaborate computers for calculation, and long computation times, while others require only limited computation, being accomplished mainly by nomographs. Almost all methods use the synoptic wind field as input for calculations. Since the fine details of the synoptic wind field are not available, local variability in waves often is underestimated by these models.

B.2.2 Wave Model Types and Parameters

In general, wave models can be considered discrete or parametric. The discrete models attempt to simulate the wave energy balance or transport equation directly, with all of the wave generation (source) terms and the wave dissipation (sink) terms. These models, dating back to Pierson et al. (210), have advanced considerably over the past twenty years. They must all use some parameterization or representation of the various source and sink terms to provide adequate results. In contrast, a class of models known as parametric wave models have evolved from the initial work of Sverdrup and Munk (209), in which the major features of a wave are derived more simply (represented in nomograph form by S-M), reducing computational cost. All rely to some degree on empiricism, relating wave characteristics to the forcing terms (wind).

As might be predicted, these two approaches have led to hybrid models, where elements of discrete models are combined with elements of the parametric models. This hybrid approach can be used to describe different elements of the wave field, or the wave field at different stages of development. There is considerable, ongoing debate over which of these two (or three) types of models is most appropriate for shallow water conditions.

The COE for instance, historically has used a parametric approach, as described in the Shore Protection Manual. Recently, however, they have been developing a discrete wave model for use in shallow water. Its performance has not yet been tested completely with field data. In contrast, much recent work has gone into improving parametric wave models. Several oil companies are now providing an intercomparison of the models to try to evaluate the performance of the different models. The results of an experiment in the early 1980's (211) showed that the differences between model results are large, and not explainable by uncertainties in meteorlogical conditions. The debate will continue as the proponents of the different models continue their theoretical development and comparison with field data (which are extremely sparse).

For the Long Island Sound case, a model should be selected which will account for finite depth effects, and not rely on deepwater relationships. Such models exist in both a discrete and parametric form. Very important in the finite depth case is a proper representation of the bottom friction term, as well as other sources and sinks. Given the variety of different models available, the fact that they all yield results distinct from one another, and the fact that there has been no definitive intercomparison because of lack of a good data set, there is considerable latitude in selection of an appropriate wave forecasting model.

B.2.3 NWS Wave Forecast Model

The National Weather Service uses a wind-wave forecast for generalized offshore wave conditions. This wave forecast is of the parametric type, based largely on empirical relationships between the size of waves generated by specific winds. It follows in the mold of the Sverdrup-Munk-Bretschneider (SMB) type methodology first developed in 1947. Three parameters required to use these nomographs are wind speed, fetch length, and wind duration. Each of these is discussed briefly below.

Wind speed suffers from need to specify average wind speed over the fetch of the storm and over the duration during which it existed. This specification is a primary weakness of the limited nomographs, since the precise details of the averaging can affect the final result. The wind speed has to be adjusted for atmspheric boundary layer effects; thus wind cannot be input simply from calculated geostrophic (or thermal) winds generated from synoptic pressure charts. Details of this correction are generally ignored in most parametric forecasts of this type.

Fetch is the distance over which the "constant" wind has been blowing. For an easterly wind in Long Island Sound, for instance, the fetch is much smaller in eastern Connecticut than in western Connecticut. The definition of the fetch is determined by some subjective decisions about the size of the pressure system causing the winds, and other such matters. The definition of fetch therefore is far from exact.

The final term needed to apply these nomograms is the duration of the wind. This must be the representative time during which the wind speed has acted over the prescribed fetch. Clearly these three parameters must be chosen carefully to make this simple forecast of wave conditions.

For the NWS purposes of providing marine forecasts for mariners, generalized wave forecasts may be adequate. However, since these simple nomograph techniques ignore all details of wave scattering and dissipation, they are not applicable to forecasting wind waves for coastal localities. Examples of the major areas of omission in the nomographs include: no bottom friction, no wave refraction, no wave reflection, no wave diffraction, lack of inclusion of a time-variable wind field and fetch length. Again, these omissions may not affect the generalized wave forecasting needs of NWS, but they are critical to the mission of accurately forecasting coastal wave fields.

For purposes of providing coastal flood warning to the residents of a coastal reach, the NWS methodology is clearly inadequate. For best results, a numerical wave forecast model is required, which includes the full effects of dissipation and scattering.

B.2.4 Elements of a LIS Wave Model

The important elements of a wave model to be considered for LIS include:

- Shallow water form
- Appropriate form of bottom friction to account for nonlinear losses
- Inclusion of wave refraction/diffraction for shallow water.
- Proven performance and reliability
- Reasonable performance in standard intercomparisons
- Reasonable cost and efficiency
- Appropriate and separate treatment of both locally-generated and swell-components.
- Some spectral form to properly account for wave-wave interactions.

Based on a survey of the field and opinions of other oceanographers in the field, one excellent choice for providing LIS wave forecasts is the hybrid wind-wave model of Graber (105).

In this hybrid model, Graber uses the shallow water form of the wave equations, applying the most advanced friction estimates to correct for finite depth effects, and incorporates refraction and shoaling. This model has been run for a variety of different locales, and a variety of different conditions, with reasonable results.

APPENDIX C: GLOSSARY OF ABBREVIATIONS

AFOS - Automation of Field Operations and Service
ALERT - Automated Local Evaluation in Real Time
ASERT - Automated State Evaluation in Real Time
BW - Bureau of Waterways (DOT)
CAFW - Committee on Automated Flood Warning
CERC- Coastal Engineering Research Center (Corps of Engineers)
COE - U.S. Army Corps of Engineers (DOA)
CSP - Connecticut State Police
DEP - Department of Environmental Protection (CT)
DOC - Department of Commerce (US)
DOT - Department of Transportation (CT)
EPA - Environmental Protection Agency
FEMA - Federal Emergency Management Agency
FIRM - Flood Insurance Rate Map
FIS - Flood Insurance Study
GOES - Geostationary Operational Environmental Satellite
IEMIS - Integrated Emergency Management Information System
LIS - Long Island Sound
MAPONY - Maritime Administration, Port of New York
MEOW- Maximum Envelope of Water
MHW - Mean High Water
MLLW - Mean Lower Low Water
MLW - Mean Low Water
MSL - Mean Sea Level
NAS - National Academy of Sciences
NAWAS - National Warning System
NERFC - Northeast River Forecast Center (NWS, NOAA)
NGVD- National Geodetic Vertical Datum (1929 datum)
NGWLMS - Next Generation Water Level Monitoring System
NMS - National Meteorological Center (NWS, NOAA, DOC)
NOAA - National Oceanic and Atmospheric Administration (DOC)
NOS - National Ocean Service (NOAA, DOC)
NRC - Natural Resources Center (DEP)
NWLON - National Water Level Observation Network
NWR - NOAA Weather Radio
NWS - National Weather Service (NOAA, DOC)
OCP - Office of Civil Preparedness (CT)
SCS - Soil Conservation Service (DOAg)
SIO - Scripps Institute of Oceanography
SLOSH - Sea, Lake and Overland Surges from Hurricanes
SPLASH- Special Program to List Amplitudes of Surges from Hurricanes
TDL - Techniques Development Laboratory (NWS, NOAA, DOC)
UCONN - University of Connecticut
UHF - Ultra High Frequency
USGS - U.S. Geological Survey (U.S. Dept. of the Interior)
VHF - Very High Frequency
WHOI - Woods Hole Oceanographic Institution
WRU - Water Resources Unit (DEP)
WSFO - Weather Service Forecast Office
WSO - Weather Service Office

APPENDIX D: REFERENCES

1. Hicks, Steacy D. 1983. Sea Level Variations for the United States, 1855-1980. National Ocean Service, NOAA, U.S. Dept. of Commerce.
2. Hicks, Steacy D. 1984. Tide and Current Glossary. National Ocean Service, NOAA, U.S. Dept. of Commerce.
3. Hicks, Steacy D. 1980. The National Tidal Convention of 1980. National Ocean Service, NOAA, U.S. Dept. of Commerce.
4. Swanson, Robert L. 1974. Variability of Tidal Datums Accuracy in Determining Datums from Short-Series of Observations. NOAA Technical Report NOS 64. National Ocean Survey, NOAA, U.S. Dept. of Commerce.
5. Coastal Area Management. 1977. Long Island Sound: An Atlas of Natural Resources. Dept. of Environmental Protection, Hartford, CT.
6. U.S. Army Corps of Engineers. 1980. Tidal Flood Profiles, New England Coastline. Hydraulics and Water Quality Section, New England Division.
7. National Ocean Service. 1984. Tide Tables: 1985 High and Low Water Predictions, East Coast of North and South America, Including Greenland. NOAA, U.S. Dept of Commerce.
8. Aubrey, D.G. and K.O. Emery. 1983. Eigenanalysis of Recent United States Sea Levels. Cont. Shelf Research, v. 2, p. 21-33.
9. Hoffman, John S., et.al. 1983. Projecting Future Sea Level Rise: Methodology, Estimates to the Year 2100, and Research Needs. U.S. Environmental Protection Agency.
10. Revelle, R. 1983. "Probable Future Changes in Sea Level Resulting from Increased Atmospheric Carbon Dioxide," from Changing Climate. Carbon Dioxide Assessment Committee, National Academy of Sciencies, Washington, DC, National Academy Press.
11. U.S. Army Coastal Engineering Research Center. 1977. Shore Protection Manual, Volume I. Corps of Engineers, Dept. of the Army.
12. New England Division. 1976. Connecticut Coastline Study: Effects of Coastal Storms. U.S. Army Corps of Engineers.
13. Bohlen, W.F., and K.B. Winnick. 1983. A Survey of Surface Waves in Long Island Sound. Prepared for the State of Connecticut, Department of Environmental Protection, Hartford.
14. Hardy, C.D. Marine Sciences Research Center, State University of New York, Stony Brook, NY.
15. Crowley, Cliff, Meteorologist In Charge, New York WSFO, NWS. Personal communication, 2/13/85 and subsequent.
16. Federal Emergency Management Agency. 1983 - 1985. Flood Insurance Studies; Wave Height Analysis Supplements, for Connecticut coastline communities, Greenwich to Stonington.
17. Hobbs, Carl H. 1970. Shoreline orientation and storm surge. Maritime Sediments 6:113-116.
18. Harris, D.L. 1963. Characteristics of the Hurricane Storm Surge. U.S. Weather Bureau, Washington D.C., Tech. Paper No. 48
19. Gentry, R.C. 1966. Nature and Scope of Hurricane Damage. Pages 229-254 in S.A. Stubbs ed. Hurricane Symposium, American Society of Oceanography, Houston.
20. Frazier, Quartermaster First Class, Long Island Sound Group, Coast Guard, New Haven. Personal communication, 9/6/85.

21. Boutilier, Carl, Chief, Navigation Branch, New England Division, U.S. Army Corps of Engineers. Personal communication, 10/3/85.
22. Warner, Captain Ken, President, Northeast Marine Pilots, Inc., Newport, RI. Personal communication, 9/6/85.
23. Monks, Captain Donald, New Haven-Bridgeport Pilots Association, Milford, CT. Personal communication, 9/9/85.
24. Water Resources Support Center. 1983. The Ports of Southern New England:- Providence, RI, Fall River, MA, New London, New Haven, & Bridgeport, CT. Port Series No. 4, U.S. Army Corps of Engineers.
25. Vaukus, Jim, Manager, Stamford Hurricane Barrier, U.S. Army Corps of Engineers, Stamford, CT. Personal communication, 2/20/86 and subsequent.
26. O'Haragan, Mike, Facilities Group, National Geodetic Information Center, NOS, NOAA, U.S. Dept. of Commerce. Personal communication, 12/5/84.
27. Deibel, Lawrence E., and Barbara A. Zumwalt. 1985. Next Generation Water Level Measurement System Program. By The Mitre Corporation for National Ocean Service, NOAA, Dept. of Commerce.
28. Tidal Bench Marks. Connecticut, New London. 1968. Coast and Geodetic Survey, Environmental Science Services Administration, U.S. Dept. of Commerece.
29. Tidal Bench Marks. Connecticut, Bridgeport. 1968. Coast and Geodetic Survey, Environmental Science Services Administration, U.S. Dept. of Commerce.
30. Lyles, Steve, Tidal Datum Section, National Ocean Service, NOAA, U.S. Dept. of Commerce. Personal communication, 8/26/85.
31. Dennam, Robert, National Ocean Service, NOAA, Dept. of Commerce, Bridgeport, CT. Personal communication, 2/85.
32. Gillette, Earl, Meteorologist in Charge, Bridgeport WSO, NWS, Stratford, CT. Personal communication, 2/13/85 and subsequent.
33. Williams, Burt, Electronics Technician, Bridgeport WSO, NWS, Stratford, CT. Personal communication, 11/28/84 and subsequent.
34. St. Clair, J.M. 1985. National Weather Service memorandum on Technical Information Package - Installation of the Data Collection Platform Handar (DCPH) System (Telephone Type). NWS, NOAA, U.S. Dept. of Commerce, Silver Spring, MD.
35. Thomas, C.E., et.al. 1983. Water Resources Data Connecticut: Water Year 1982. U.S. Geological Survey Water-Data Report CT-82-1. Water Resources Division, U.S. Geological Survey, Hartford.
36. Cervione, Mike, Water Resources Division, USGS, Hartford, CT. Personal communication, 8/9/85 and subsequent.
37. Shepard, Tom, Water Resources Division, USGS, Hartford, CT. Personal communication, 8/9/85 and subsequent.
38. Rigatti, George, Water Resources Division, USGS, South Windsor, CT. Personal communication, 2/21/86 and subsequent.
39. Mirick, Robert, Reservoir Control Center, New England Division, U.S. Army Corps of Engineers, Waltham, MA. Personal communication, 10/11/85.
40. Finigan, Joseph, Chief, Reservoir Control Center, New England Division, U.S. Army Corps of Engineers, Waltham, MA. Personal communication, 3/5/86.
41. National Ocean Service. 1985. Index of Tide Stations: United States of America and Miscellaneous Other Locations (Rough Draft). NOAA, U.S. Dept. of Commerce.
42. Dunn, Gordon E., and Banner I. Miller. 1960. Atlantic Hurricanes. Louisiana State University Press.
43. Neumann, Charles J., et.al. 1981. Tropical Cyclones of the North Atlantic

Ocean, 1871-1980 (with updates through 1984). National Climatic Center, NWS, Asheville, N.C.

44. Neumann, C.J. and M.J. Pryslak. 1981. Frequency and Motion of Atlantic Tropical Cyclones. NOAA Technical Report NWS 26. National Hurricane Center, Coral Gables, FL.

45. Long Island Regional Planning Board. 1984. Hurricane Damage Mitigation Plan for the South Shore of Nassau and Suffolk Counties, New York. Long Island Regional Planning Board, Hauppauge, NY.

46. Dewberry & Davis. 1982. Tidal Flood Profiles for the Connecticut Shoreline of Long Island Sound. Prepared for the Federal Emergency Management Agency.

47. New England Division. 1982. Regulation Manual, Stamford Hurricane Barrier, Stamford, Connecticut. U.S. Corps of Engineers, Waltham, MA.

48. Mather, J.R., et.al. 1965. Coastal Storms of the Eastern United States. Journal of Applied Meteorology, 3:693-706.

49. Federal Emergency Management Agency. 1980. Flood Insurance Study, Town of Old Lyme, Connecticut.

50. Federal Emergency Management Agency. 1983. Flood Insurance Study, Supplement - Wave Height Analysis, Town of Old Lyme, Connecticut.

51. National Academy of Sciences. 1977. Methodology for Calculating Wave Action Effects Associated with Storm Surges. Washington, DC.

52. Rummel, Cynthia J., and G.J. Hudak. 1984-1985. Flood Vulnerability Assessment (for 24 coastal Connecticut municipalities). Natural Resources Center, Department of Environment Protection, Hartford, CT.

53. Williams, Allan N., Natural Resources Center, Department of Environmental Protection, Hartford, CT. Personal communication, 2/13/85 and subsequent.

54. National Weather Service. 1981. Automated Local Evaluation in Real Time: A Cooperative Flood Warning System for Your Community. Hydrologic Services Division, National Weather Service, Western Region, Salt Lake City, UT.

55. Curtis, David C. 1980. Flash Floods — Communities Can Help Themselves Prepare. Presented at the 1980 NAR-ASAE Annual Meeting, Eastern Connecticut State College, Willimatic, CT.

56. Owen, James H., and M. Wendell. 1981. Implementation Aspects of Flood Warning and Preparedness Planning Alternatives. Prepared for Institute for Water Resources, Water Resources Support Center, U.S. Army Corps of Engineers. Fort Belvoir, VA.

57. National Advisory Committee on Oceans and Atmosphere. 1983. The Nations's River and Flood Forecasting and Warning Service. A Special Report to the President and the Congress. Washington, DC.

58. Owen, James H. 1979. Information for Local Officials on Flood Warning Systems. Prepared for National Weather Service, NOAA, U.S. Dept. of Commerce.

59. Hydrology Subcommittee of the Federal Interagency Advisory Committee on Water Data. 1985. Guidelines on Community Local Flood Warning and Response Systems.

60. Oyekan, Taiwo A., and Jerry R. Rogers. 1983. Flood Forecasting/Warning System for Ibadan, Nigeria. Presented at American Water Resources Association, International Symposium on Hydrometeorology. San Francisco, CA.

61. Curtis, David C. President, International Hydrological Services, Sacramento, CA. Personal communication, 2/85 and subsequent.

62. Curtis, David C. 1982. ALERT for Connecticut. Northeast River Forecast Center, National Weather Service, Bloomfield, CT. Presented at the

Connecticut Flood Management Workshop, Meriden, CT.
63. Lubbers, Mark. Director, Environmental Protection Board, Stamford, CT. Personal communication, 2/85 and subsequent.
64. Committee on Automated Flood Warning. 1985. Automated Flood Warning in Connecticut: A Master Plan.
65. Soil Conservation Service. 1985. Connecticut Flood Warning System, Bidders Package. SCS, U.S. Dept. of Agriculture, Storrs, CT., in cooperation with Department of Environmental Protection, CT.
66. Garlitz, Nancy M. 1985. "Automated Flood Warning Reduces Flood Damages", Soil and Water Conservation News, Jan., 1985. pp 3-5.
67. Renn, Phillip. Water Resources Coordinator, Soil Conservation Service, U.S. Dept. of Agriculture, Storrs, CT. Personal communication, 8/26/85 and subsequent.
68. Laro, Roland. Meteorologist in Charge, Hartford Weather Service Office, NWS, Windsor Locks, CT. Personal communication, 2/27/86.
69. Thomas, Steven, Deputy Director, New York Weather Service Forecast Office, NY,NY. personal communication, 9/26/85.
70. Duty Officer (individual unknown), U.S. Coast Guard, Long Island Sound Group, New Haven, CT. Personal communication, 9/6/85.
71. Schaeffer, Wilson A., Techniques Development Laboratory, Office of Systems Development, National Weather Service, Silver Spring, MD. Personal communication, 1/22/85 and subsequent.
72. Jarvinen, Brian, National Hurricane Center, National Weather Service, Coral Gables, FL. Personal communication, 1/24/85 and subsequent.
73. Pore, N.A., W.S. Richardson, and H.F. Perrotti. 1974. Forecasting Extra-tropical Storm Surges for the Northeast Coast of the United States. NOAA Technical Memorandum NWS TDL-50, Washington, D.C., 68 pp.
74. Baskerville, Robert, New York Weather Service Forecast Office, NY, NY. Personal communication, 9/18/85.
75. Auciello, Jene, Boston Weather Service Forecast Office, Boston, MA. Personal communication, 10/11/85.
76. National Weather Service. 1981. NOAA Weather Radio. NOAA/ PA 76015.
77. Carter, Michael T. 1983. Probability of Hurricane/Tropical Storm Conditions: A User's Guide for Local Decision Makers. Severe Weather Branch, National Weather Service, NOAA, U.S. Dept. of Commerce.
78. L.R. Johnston Associates. 1983. Realizing the Risk: A History of the June 1982 Floods in Connecticut. Prepared for the Natural Resources Center, CT Department of Environmental Protection.
79. Gibb, Paul, Office of Civil Preparedness, Hartford, CT. Personal communication, 9/21/85 and subsequent.
80. Kusako, Herb, CT Office of Civil Preparedness, Region I, Fairfield, CT. Personal communication, 10/17/85.
81. Melendez, Pedro, CT Office of Civil Preparedness, Region II, New Haven, CT. Personal communication, 10/7/85.
82. Scelora, Anthony, CT Office of Civil Preparedness, Region IV, Colchester, CT. Personal communication, 10/7/85.
83. Office of Civil Preparedness. 1981. Emergency Operations Plan. CT Office of Civil Preparedness, Hartford, CT.
84. Lappe, Kenneth, CT Office of Civil Prparedness, Hartford, CT. Personal communication, 10/18/85.
85. Conlea, Wilbur, Civil Preparedness Director, Danbury, CT. Personal communication, 10/17/85.
86. Darrow, Mary Ann, Civil Preparedness Director, Waterford, CT. Personal communication, 10/17/85.

87. Johnson, Fred, Civil Preparedness Director, East Lyme, CT. Personal communication, 10/18/85.
88. Sawyer, Carl, Civil Preparedness Director, Town of Groton, CT. Personal communication, 10/17/85.
89. U.S. Army Corps of Engineers, New England Division. 1974. Long Island, Sound Interim Memo No. COE-2, Tidal Hydrology. Waltham, MA.
90. Richardson, William S. 1978. Extratropical Storm Surge Forecasts for the U.S. East Coast. NWS Technical Procedures Bulletin No. 226.
91. Jelesnianski, C.P., 1972. SPLASH (Special Program to List Amplitudes of Surges from Hurricanes), I. Landfall storms. NOAA Technical Memorandum, NWSS TDL-46, 52 pp.
92. Jelesnianski, C.P., 1974. SPLASH--Special Program to List Amplitude of Surge from Hurricane--Part II--General track and variant storm conditions. NOAA, Technical Memorandum, NWS TDL-52.
93. Jelesnianski, C.P., J. Chen, W.A. Shaffer, and A.J. Gilad, ND. SLOSH--a hurricane storm surge forecast model. Techniques Development Laboratory, National Weather Service, NOAA, Silver Spring, MD.
94. National Weather Service, Techniques Development Laboratory. 1985 (Draft). Untitled (Technical Description of SLOSH). Silver Spring, MD.
95. Wiggert, Victor, National Hurricane Center, National Weather Service, Coral Gables, FL. Personal Communication, 12/20/85.
96. Andress, Harold, Federal Emergency Management Agency, Washington, DC. Personal communication, 1/22/85 and subsequent.
97. Coleman, Rick, National Weather Service, Techniques Development Laboratory, Silver Spring, MD. Personal communication, 1/22/85.
98. Titus, Temp. Testing and Evaluation Section, National Weather Service, Silver Spring, MD. Personal communication, 9/85.
99. Gordon, R.B. and M.L. Spaulding, 1979. A nested numerical tidal model of the southern New England bight. Ocean Engineering Dept., Univ. of Rhode Island, N79-14698, 55 pp.
100. Spaulding, M.L. and R.B. Gordon, 1982. A nested numerical tidal model of the southern New England bight. Ocean Engineering, v. 9, p. 107-126.
101. Spaulding, M.L., 1984. A vertically averaged circulation model using boundary-fitted coordinates. J. Phys. Oceanog., v. 14, p. 973-982.
102. Braatz, B.V. and D.G. Aubrey, submitted. Recent sea-level changes along eastern North America.
103. Peltier, W.R., submitted. Deglaciation induced vertical motion of the North American continent. Jour. Geophys. Research.
104. U.S. Army Corps of Engineers. 1984. Shore Protection Manual, 4th ed., 2 vols., U.S. Army Waterways Experiment Station, Coastal Engineering Research Center, U.S. Govt. Printing Office, Washington, D.C.
105. Graber, H.C., 1984. A parametric wind-wave model for arbitrary water depths. Mass. Inst. Tech., Doctoral Thesis, Cambridge, MA, 310 pp.
106. National Academy of Sciences. 1977. Methodology for Calculating Wave Action Effects Associated with Storm Surge. Washington, DC.
107. Leupold & Stevens, Inc. 1978. Stevens Water Resources Data Book. Beaverton, OR.
108. U.S. Coast and Geodetic Survey. 1977. Manual of Tide Observations. Publication 30.1.
109. Mero, Thomas N., and Alfred Zulueta. 1979. Water Level Measurement Systems Technology Survey. National Ocean Survey, Test and Evaluation Laboratory.
110. Various product descriptions and specification sheets from numerous vendors and manufactures.

111. Bartex, Inc. 1985. Product descriptions and specifications for AQUATRAK 1100 and 2000 acoustic tide gage.
112. Barnes, Harry, President, Bartex, Inc. Personal communication, 1/22/85 and subsequent.
113. Mero, T.N., 1981. Aquatrak model LG-1100 water level gage operating range and fouling effects. NOAA ESO Tech. Report TE3-81-010, 5 pp.
114. Libraro, P.J., 1980. Evaluation of the Aquatrak model LG-1101-01 precision water level measurement system. NOAA ESO Technical Report TE3-81-002.
115. Seymour, Richard J., M.H. Sessions, and David Castel. 1985. Automated Remote Recording and Analysis of Coastal Data. Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 111, No. 2.
116. Colton, Donald E., Vice President, Systems Development, International Hydrological Services, Sacramento, CA. Personal communication, 2/86.
117. Holland, Mel, Handar, Inc., Sunnyvale, CA. Personal communication, 9/19/85.
118. Federal Emergency Management Agency. 1984. A Guide for Hurricane Preparedness Planning for State and Local Officials. CPG 2-16.
119. Fach, Skip, U.S. Army Corps of Engineers, Baltimore, MD. Personal communication, 12/10/85.
120. Hughes, Rebecca, Water Resources Administration, Maryland Department of Natural Resources, Annapolis, MD. Personal communication, 2/85 and subsequent.
121. Sharrocks, Fred, Federal Emergency Management Agency. Personal communication, 10/8/85 and subsequent.
122. Old, Kenneth, B., U.S. Army Engineer District, Flood Plain Management Branch, Wilmington, NC. Personal communication, 12/85.
123. Hess, Richard, National Ocean Service. Personal communication, 1/17/85.
124. Lapine, Louis, National Ocean Service. Personal communication, 9/10/85 and subsequent.
125. Hays, John, National Ocean Service. Personal communication, 10/28/85.
126. McCarthy, Kevin, Meteorologist, Eastern Region Headquarters, National Weather Service, Garden City, NY. Personal communication, 2/14/85.
127. Handar, Inc. 1984. Operating and Service Manual for 540A Multiple Access Data Acquisition System, 560A Hydrologic Data Collection System, and 545A Programming Set. Sunnyvale, CA.
128. Schiesl, Joseph, Data Systems, National Weather Service. Personal communication.
129. Jaske, Robert, Federal Emergency Management Agency. Personal communication, 10/18/85.
130. Federal Emergency Management Agency. 1984. Computer Capabilities Developed for Integrated Emergency Management Information Program. FEMA Newsletter, Nov/Dec, 1984.
131. Federal Emergency Management Agency. 1985. More about IEMIS. FEMA Newsletter, May/June, 1985.
132. Jaske, Robert T. 1985. FEMA's Integrated Emergency Management Information System (IEMIS). Proc. American Meteorological Society, Jan. 8, 1985.
133. Federal Emergency Management Agency. 1985. Integrated Emergency Management Information System (IEMIS): Development and Deployment Plan (Draft).
134. Melendez, Pedro, Connecticut Office of Civil Preparedness, Hartford, CT. Personal communication, 10/7/85.
135. Castel, David, Scripps Institute of Oceanography, La Jolla, CA. Personal communication, 2/20/86 and subsequent.
136. Lilly, Kenneth, Chief Meteorologist, Marine Services, Meteorological Services Division, Western Region Headquarters, National Weather Service,

Salt Lake City, UT. Personal communication, 2/20/86.

137. U.S. Army Corps of Engineers, and California Department of Boating and Waterways. 1986. Coastal Data Information Program, Monthly Report, December 1985. Monthly Summary Report No. 119.

138. Seymour, R.J., et. al. 1985. Coastal Data Information Program, Ninth Annual Report, January 1984 through December 1984. Scripps Institute of Oceanography, La Jolla, CA.

139. Lilyquist, Alan, Coastal Resources Specialist, New York Department of State, Albany, NY. Personal Communication, 3/85 and subsequent.

140. Canata, Barbara, The Maritime Association of the Port of New York, New York, NY. Personal communication, 3/1/85 and subsequent.

141. Cretan, Nick C., The Maritime Association of the Port of New York, New York, NY. Personal communication, 3/15/85 and subsequent.

142. The Maritime Association of the Port of New York. Undated. Tidal Gauge System. (unpublished program description).

143. Prindiville, William, Manager, Vessel Operations, Sea-Land Service, Inc., Elizabeth, NJ. Personal communication, 3/20/85 and subsequent.

144. New York State Department of State. Undated. The Tidal Gauge System (brochure).

145. Visel, Tim, Connecticut Marine Advisory Service, Marine Sciences Institute, Groton, CT. Personal communication, 10/3/85.

146. Peters, Captain Tom, Sandy Hook Pilots Association, Sandy Hook, NJ. Personal communication, 9/23/85.

147. Becker, Captain George, Sandy Hook Pilots Association, Sandy Hook, NJ. Personal communication, 9/24/85.

148. Kramer, George, McAlister Brothers, Inc., New York, NY. Personal communication, 9/23/85.

149. Curll, Dan, American Waterway Operators Association, New York, NY. Personal communication, 9/18/85.

150. Wolff, Paul M., and Dane Konop. 1984. Predicting Water Circulation in Delaware Bay and River: NOAA's New Approach. Sea Technology, Sept. 1984.

151. Mellor, G.L., Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ. Personal communication, 1/86.

152. Perkins, Don, Assistant Executive Director, Marine Board, National Research Council, National Academy of Sciences, Washington, DC. Personal communication, 2/21/86.

153. Stoll, Jeffrey E. 1983. Accomodating the Tides. Surveyor, May, 1983, pp. 16-21.

154. Guth, Jack, President, Sea and Meteorology, Inc., Herndon, VA. Personal communication, 1/10/85 and subsequent.

155. Sea and Meteorology, Inc. Undated. Technical Description of real-time tide and wind gage system.

156. Dunlap, Craig. 1984. Computerized harbor Gauges Advocated. The Journal of Commerce, May 1, 1984.

157. Hazen, Frank, President, Hazen Tide Gauge International, Tacoma, WA. Personal communication, 1/10/85 and subsequent.

158. Howell, Gary. 1980. Florida Coastal Data Network. Proceedings of the Seventeenth Coastal Engineering Conference, Volume 1, pp. 421-431.

159. Howell, Gary L. 1978. A Microprocessor Based Underwater Data Acquisition System. Coastal & oceanographic Engineering Department, College of Engineering, University of Florida, Gainesville, FL.

160. Metha, Dr., College of Engineering, University of Florida, Gainesville, FL. Personal communication, 10/10/85.

161. Perlin, Mark, College of Engineering, University of Florida, Gainesville, FL. Personal communication, 10/10/85.
162. Howell, Gary L., U.S. Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg, MS. Personal communication, 10/10/85.
163. Guice, Wade, Director, Harrison County Civil Defense, Gulfport, MS. Personal communication, 9/18/85 and subsequent.
164. Harrison County Civil Defense Council. 1985. Harrison County Water Level Monitoring System, Requirements Specifications (Draft). Gulfport, MS.
165. N.B.A. (Controls) Ltd. 1985. Dial-a-Surge. Current Affairs, The Newsletter of NBA (Controls) Ltd., Autumn '85.
166. Synergetics International, Inc. 1984. Synergetics Awarded Contract for Ganges River/Bay of Bengal Installation. How GOES It? (Synergetics Newsletter). Boulder, CO.
167. Synergetics International, Inc. 1985. Experience Profile. Boulder, CO.
168. Andress, Bud. 1985. The Federal Emergency Management Agency (FEMA) Hurricane Preparedness Program. Presented at the "Cities on the Beach" Conference on the Management of Developed Coastal Barriers. Jan. 17, 1985, Virginia Beach, VA.
169. Bray, William, Civil Preparedness Director, Fairfield, CT. Personal communication, 2/13/85.
170. Healey, Chief, Civil Preparedness Director, Milford, CT. Personal communication, 2/13/85.
171. Federal Insurance Administration, Federal Emergency Management Agency. 1981. Field Manual for Estimating Wave Heights in Coastal High Hazard Areas in Atlantic and Gulf Coast Regions.
172. Federal Insurance Administration, Federal Emergency Management Agency. 1981. Users Manual for Wave Height Analysis.
173. National Academy of Sciences. 1977. Methodology for Calculating Wave Action Effects Associated with Storm Surges.
174. Various oceanographic researchers. Personal communication.
175. Sessions, Meredith, Scripps Institute of Oceanography, La Jolla, CA. Personal communication, 3/11/85.
176. Roper, Ted, Sales Manager, Sierra Misco, Inc., Berkely, CA. Personal communication, 3/11/86.
177. Smith, Robert, Assistant Director, Planning Section, Water Compliance Unit, CT Department of Environmental Protection, Hartford, CT. Personal communication, 10/17/85 and subsequent.
178. Stacey, Paul, Environmental Analyst, Planning Section, Water Compliance Unit, CT Department of Environmental Protection, Hartford, CT. Personal communication, 3/11/86.
179. Morrissey, Tom, Senior Sanitary Engineer, Planning Section, Water Compliance Unit, CT Department of Environmental Protection, Hartford, CT. Personal communication, 3/11/86.
180. Conel Cellular, Inc., Norwalk, CT. Personal communication, 3/11/86.
181. Morton, Bohlen, and Aubrey. 1985.
182. Vitello, Petty Officer, Aides to Navitation Team, Long Island Sound Group, U.S. Coast Guard, New Haven, CT. Personal communication, 3/5/86.
183. Schillumeit, Cheif, Aides to Navitation Team, Long Island Sound Group, U.S. Coast Guard, New Haven, CT. Personal communicatiion, 3/7/86.
184. Renn, Phillip A. 1986. Minutes of February 3, 1986 meeting of the Committee on Automated Flood Warning. Soil Conservation Service, Storrs, CT.

185. Mendell, Todd, Flash Flood Hydrologist, Northeast River Forecast Center, National Weather Service, Bloomfield, CT. Personal communication, 10/2/85 and subsequent.

186. Tabaco, Joe, ADP Manager, Eastern Region Headquarters, National Weather Service, Garden City, NY. Personal communication, 2/27/86.

187. Boon, J.D., C.S. Welch, H.S. Chen, R.J. Lukens, C.S. Fang, and J.M. Zeigler, 1978. Storm surge height-frequency analysis and model prediction for Chesapeake Bay. Special Report no. 189, volume I, Virginia Insitute of Marine Science, Gloucester Point, VA., 155 pp.

188. Wilson, B.W., 1957. Hurricane Wave statistics for the Gulf of Mexico. Beach Erosion Board, Department of the Army, Technical Memorandum No. 98.

189. Nihoul, J.C.J. (ed.), 1979. Marine forecasting--predictability and modelling in ocean hydrodynamics. Elsevier, Amsterdam, 493 pp.

190. Pagenkopf, J.R. and B.R. Pearce, 1975. Evaluation of techniques for numerical calculation of storm surges. Massachusetts Institute of Technology, Ralph M. Parsons Laboratory for Hydrodynamics, Report no. 199, 120 pp.

191. Pearce, B.R., 1972. Numerical calculation of the response of coastal waters to storm systems. Tech. Report no. 12, Coastal and Oceanographic Engineering Lab, Univ. of Florida, Gainesville, FL.

192. Connor, J.J. and J.D. Wang, 1973. Mathematical models of the Massachusetts Bay, Part I: Finite element modeling of two-dimensional hydrodynamic circulation. Tech. Report no. 172, Ralph M. Parsons Laboratory.

193. Wang, J.D. and J.J. Connor, 1975. Mathematical modeling of near coastal circulation. Mass. Institute of Technology, Ralph M. Parsons Laboratory Technical Report no. MITSG-75-13.

194. Thacker, W.C., 1977. Irregular grid finite-difference techniques: simulations of oscillations in shallow circular basins. J. Phys. Ocean., v. 7, p. 284-292. Thacker, W.C., 1977. Reply. Jour. Phys. Oceanog., v. 7, p. 933-934.

195. Wang, J.D., 1977. Comments on "Irregular grid finite-difference techniques: simulations of oscillations in shallow circular basins". Jour. Phys. Oceanog., v. 7, p. 932-933.

196. Johnson, B.H., 1982. Numerical modeling of estuarine hydrodynamics on a boundary fitted coordinate system. Numerical Grid Generation, J. Thompson (ed.), Elsevier, p. 409-436.

197. Thompson, J.F., F.C. Thames, and C.W. Mastin, 1977. TOMCAT--a code for numerical generation of boundary-fitted curvilinear coordinate systems on fields containing any number of arbitrary two-dimensional bodies. Jour. Computational Physics, v. 24, p. 274-302.

198. Thacker, W.C., 1978. Comparison of finite-element and finite-difference schemes. Part 1: one-dimensional gravity wave motion. J. Phys. Oceanog., v. 8, p. 284-292.

199. Thacker, W.C., 1978. Coomparison of finite-element and finite-difference schemes. Part II: Two-dimensional gravity wave motion. J. Phys. Oceanog., v. 8, p. 680-689.

200. Grant, W.D. and O.S. Madsen, 1979. Combined wave and current interaction with a rough bottom. Jour. Geophys. Research, v. 84, p. 1797-1808.

201. Grant, W.D. and O.S. Madsen, 1982. Movable bed roughness in unsteady oscillatory flow. Jour. Geophys. Res., v. 87, p. 469-481.

202. Reid, R.O. and B.R. Bodine, 1968. Numerical model for storm surges in Galveston Bay. Jour. of the Waterways and Harbors Division, ASCE,

v. 94, WW1, Proc. Paper 5805, 33-57.
203. Chapman, D.C., in press. On the numerical treatment of cross-shelf open boundaries in a barotropic coastal ocean model. Jour. Physical Oceanography.
204. Laevastu, T. and R. Callaway, 1974. Computation of tides, currents, and dispersal of pollutants in New York Bight from BIS to Atlantic City with large grid size, single and two-layer hydrodynamical numerical models. Envi. Pred. Res. Fac., Naval Post Grad. School, Monterey, CA, Tech note 4-74.
205. Leendertse, J.J. and S.K.Liu, 1977. A three dimensional model for estuarine and coastal seas, IV: Turbulent energy calculation. Rand Corp., Santa Monica, CA. Report R-2187-OWRT.
206. Beauchamp, C.H. and M.L. Spaulding, 1978. Tidal circulation in coastal seas--verification of mathematical and physical models in hydraulic engineering. Proc. of the 26th Ann. Hydraulics Div. Specialty Conf., ASCE, p. 518-528.
207. Murphy, M., 1978. Personal communication referenced in Spaulding and Gordon, 1982 (100).
208. Jelesnianski, C.P., 1970. Bottom stress time-history in linearized equations of motion of storm surge. Monthly weather review, v. 98, p. 462-478.
209. Sverdrup, H. and W. Munk, 1947. Wind, sea and swell: Theory of Relations for forecasting. Hydrographic Bureau Publication 601. U.S. Navy Hydrographic Office, Washington, D.C. 44 pp. + appendices.
210. Pierson, W.J, L.J. Tick and L. Baer, 1966. Computer based procedures for preparing global wave forecasts and wind field analysis capable of using vave data obtained from spacecraft, in Proceedings of 6th Symposium on Naval Hydrodynamics, Washington, D.C., 499 pp.
211. SWAMP, 1985. Ocean Wave Modeling. Plenum Press, NY, 256 pp.